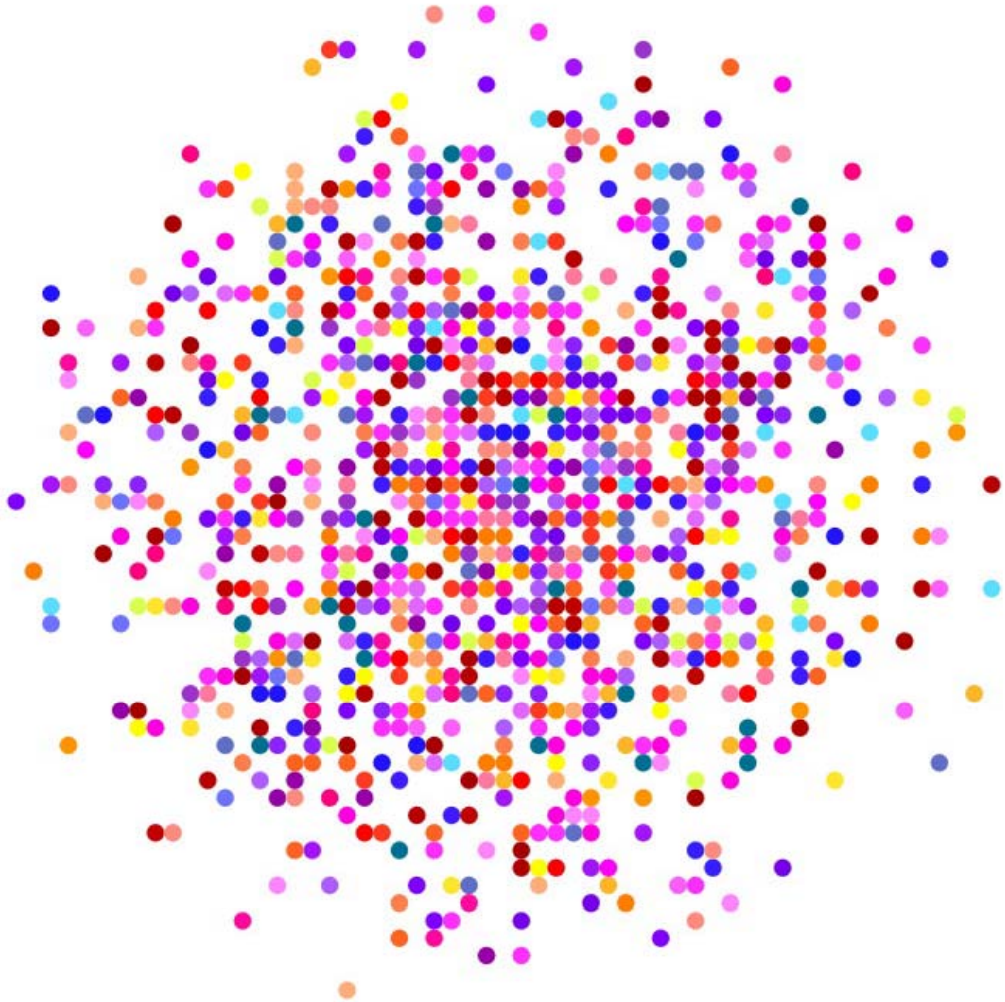
Structure Aspects of Direct and Sequential Two-Nucleon Transfer Reactions -- Alex Brown and Ian Thompson



NSCL

1.E.1:
2.G

Nuclear Physics **A302** (1978) 186–204; © *North-Holland Publishing Co., Amsterdam*
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LEVELS OF ^{52}Fe STUDIED WITH THE (p, t) REACTION †

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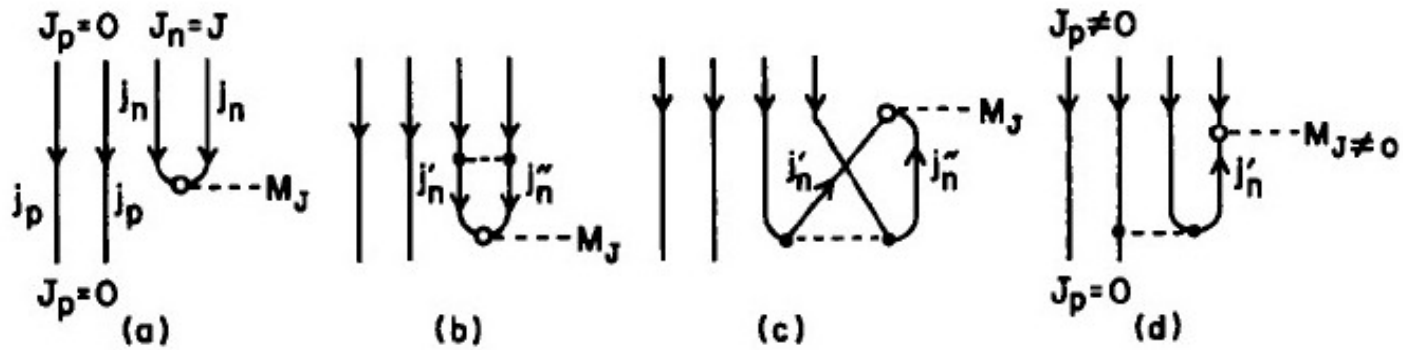
Received 28 December 1976
(Revised 2 March 1978)

Abstract: The ^{54}Fe(p, t)^{52}Fe reaction at 45 MeV has been used to study states of ^{52}Fe. Characteristic *L*-transfers in the angular distributions were used to assign ≈ 40 spins and parities. An $f_{7/2}$ shell model, with admixtures calculated in first-order perturbation theory, successfully accounts for both the location and strength of many of the observed levels.

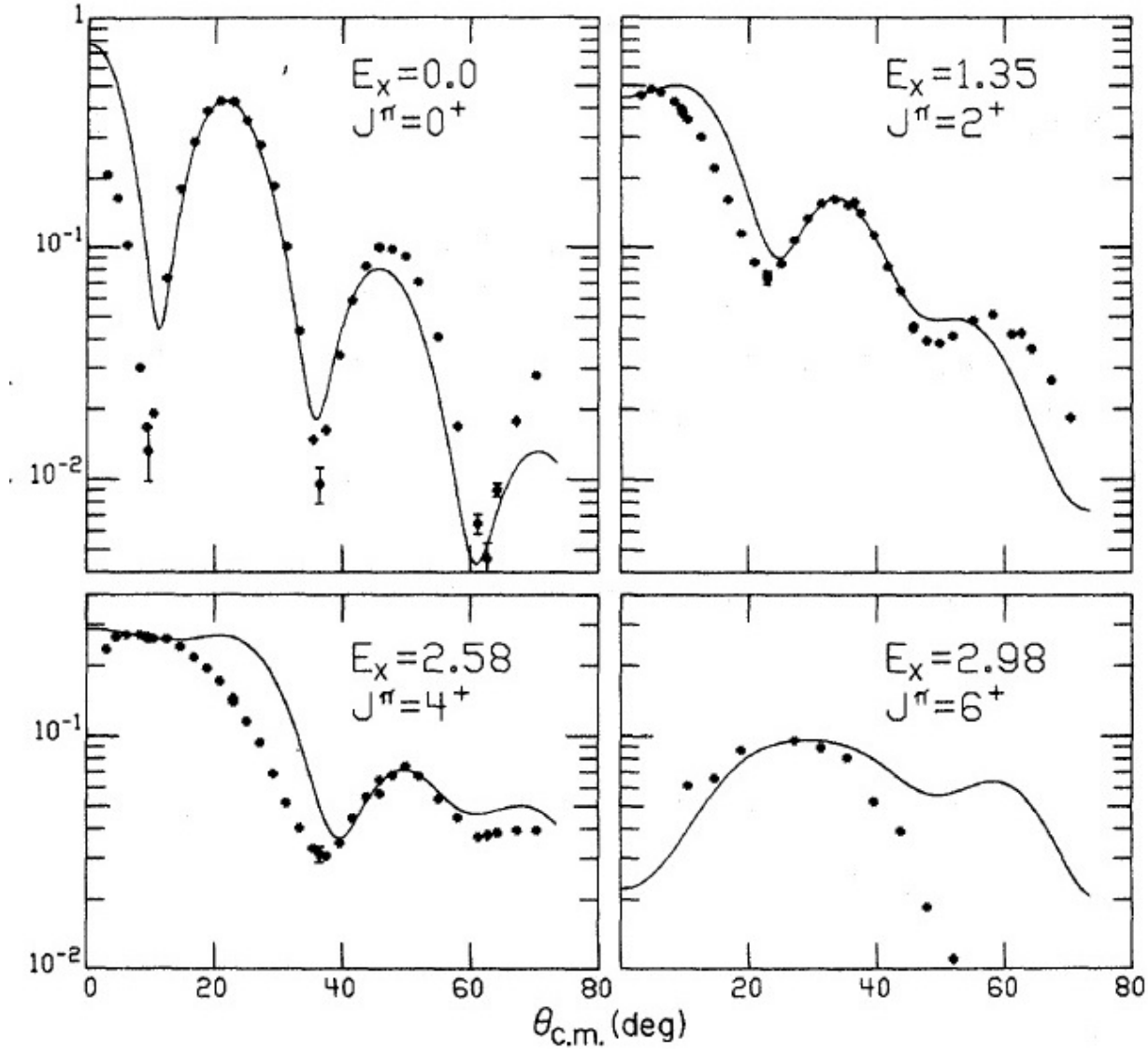


$$\frac{S^{\frac{1}{2}}(j'_n j''_n)}{(2J+1)^{\frac{1}{2}}} = \frac{-\langle j_n^2 J | V | j'_n j''_n J \rangle}{|\mathscr{E}(j'_n) + \mathscr{E}(j''_n) - 2\mathscr{E}(j_n)|}$$

TABLE 3

Normalization factors used in the DWBA analysis and calculated enhancement factors

J^π	εD_0^2 exp	fp orbitals		sd-fp-$g_{9/2}$ orbitals	
		ε	D_0^2 [c]	ε	D_0^2 [c]
0^+	93 [a]	2.16	43	4.33	21
2^+	44 [a]	1.49	30	2.26	19
4^+	22 [a]	1.10	20	1.32	16
6^+	16 [b]	1.00	16	1.03	16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J^π=0$^+$
E_x=1.35
J^π=2$^+$
E_x=2.58
J^π=4$^+$
E_x=2.98
J^π=6$^+$
1
10^{-1}
10^{-2}
0
20
40
60
80
$\theta_{c.m.}$ (deg)

IV. DISTORTED-WAVE CALCULATIONS

Distorted-wave calculations were carried out using the code DWUCK72.[14] Two different sets of proton parameters were used, one due to Becchetti and Greenlees[15] and the other due to Perey.[16] Almost 30 different sets of triton optical parameters, taken from a variety of sources,[2, 17-19] with real well depths ranging from 113 to 215 MeV were tried in an attempt to get a good fit to the low-lying states. The proton optical parameters and some of the more promising triton parameters are shown in Table II.

1970's

1) Wavefunctions were rather primitive.

2) Optical potentials for p and t not well known.

3) Claim that two-step (t,d) (d,p) was important.

4) Calculations were not absolute and had to normalized by factors of up to 10 to give agreement data (unhappyness factors)

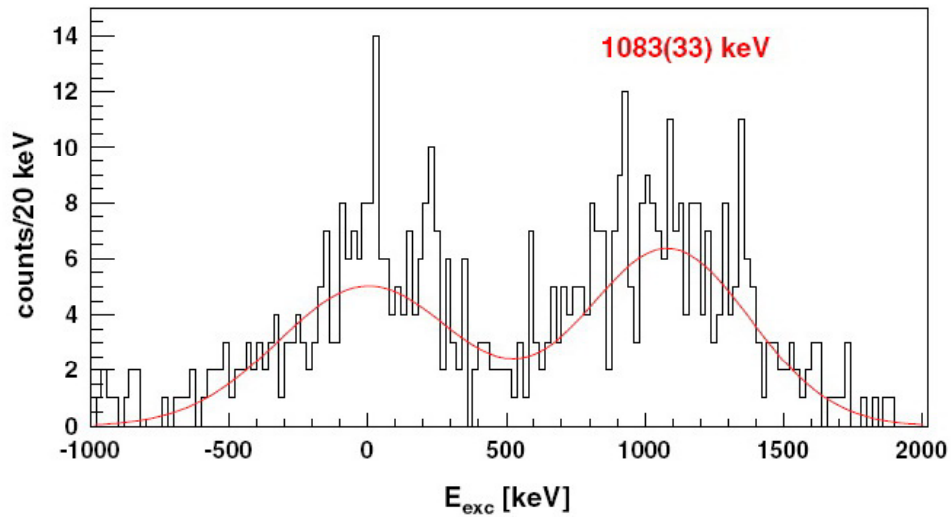
5) Pairing correlations are certainly important for J=0 (p,t)

$^{30}Mg(t,p)^{32}Mg$

Selected for a Viewpoint in *Physics*
PRL **105,** 252501 (2010) PHYSICAL REVIEW LETTERS week ending 17 DECEMBER 2010

Discovery of the Shape Coexisting 0^+ State in ^{32}Mg by a Two Neutron Transfer Reaction

K. Wimmer,[1] T. Kröll,[1,*] R. Krücken,[1] V. Bildstein,[1] R. Gernhäuser,[1] B. Bastin,[2] N. Bree,[2] J. Diriken,[2] P. Van Duppen,[2] M. Huyse,[2] N. Patronis,[2,†] P. Vermaelen,[2] D. Voulot,[3] J. Van de Walle,[3] F. Wenander,[3] L. M. Fraile,[4] R. Chapman,[5] B. Hadinia,[5] R. Orlandi,[5] J. F. Smith,[5] R. Lutter,[6] P. G. Thirolf,[6] M. Labiche,[7] A. Blazhev,[8] M. Kalkühler,[8] P. Reiter,[8] M. Seidlitz,[8] N. Warr,[8] A. O. Macchiavelli,[9] H. B. Jeppesen,[9] E. Fiori,[10] G. Georgiev,[10] G. Schrieder,[11] S. Das Gupta,[12] G. Lo Bianco,[12] S. Nardelli,[12] J. Butterworth,[13] J. Johansen,[14] and K. Riisager[14]



10.5(7) mb 6.5(5) mb

Fresco – Ian Thompson

j2.in
C:/aw/0000/fresco/sdp/m/

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   iter=2 nnu=36  chans=1 xstabl=1 smats=2
   elab=   5.400 /

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&pot kp=12 type= 1 p(1:7)=  100.000  0.9500  0.6500  0.0000
             0.0000  0.0000
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Page 2/2
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  &cfp  in= 2 ib=  3 ia=  1 kn=  7 a=   0.7071 /
  &cfp  in= 2 ib=  4 ia=  1 kn=  9 a=   0.7071 /
  &cfp /
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p)
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&coupling /
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brown

Part of Angelo Signoracci's thesis (2011) used this for $^{30}Mg(p,t)^{32}Mg$

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Back Forward Reload Stop http://www.int.washington.edu/PROGRAMS/11-2d/

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Report on Challenges for Nuclear Reaction Theory

Talks online

Seminar Schedules

Exit report

Application form

INT Program INT-11-2d

Interfaces between structure and reactions for rare isotopes and nuclear astrophysics

August 8 - September 2, 2011

Applications

If you are interested in this program, please fill out an application form. Application and visit related correspondence should be directed to the program coordinator Laura Lee. Scientific correspondence should be directed to Alex Brown. Local support will be provided for accepted participants.

Overview

The goal of this program is to identify and understand the problems that need to be solved in the area of theory for reactions with rare isotopes that are required for planning experiments for FRIB (the Facility for Rare Isotopes) and understanding their results in terms of nuclear structure and applications to nuclear astrophysics. The program will:

> Bring together reaction and structure theorists who will work together to identify specific needs of reaction theory and propose paths for their solutions and implementation.
>
> Find ways to to make the computational tools of reaction theory accessible to the community.

http://www.int.washington.edu/PROGRAMS/11-2d/

1) Report on Challenges for Nuclear Reaction Theory

2) Talks online

3) Mirror websites for reaction codes

http://www.nndc.bnl.gov/codes/

http://www.nscl.msu.edu/~brown/reaction-codes/home.html

National Nuclear Data Center

BROOKHAVEN NATIONAL LABORATORY

Home

NNDC Databases: ENDF | CSISRS | Sigma | NuDat | NSR | XUNDL | ENSDF | MIRD

Search the NNDC:

Go

- NNDC Site Index
- Resources
- Reaction Codes (MSU website)
- INT Program INT-11-2d
- ENDF Checking & Utility Codes
- ENSDF Analysis and Utility Programs

Nuclear Theory Codes

The collection of nuclear theory codes is available at the National Nuclear Data Center. The Center will provide codes per user request, however, we do not have resources for technical support. NNDC also provides access to ENDF Checking & Utility Codes and ENSDF Analysis and Utility Programs.

Reaction Codes

This project was initiated by the INT Program on Interfaces between structure and reactions for rare isotopes and nuclear astrophysics, August 8 - September 2, 2011.

This database is maintained by Alex Brown. User help beyond that contained in the links is not provided.
Many codes are also documented by the NEA website for computer programs for nuclear models and reactions. There is an IAEA website for optical model parameters.

Code	Purpose	Downloads	Documentation
Fresco	Coupled-reaction channels	source	manual getting started input examples
XFRESCO	Graphical interface for Fresco	source	
Fr2in	Creates two-nucleon transfer input for Fresco	source	manual input example
faCE	Three-body Faddeev with core excitations	source	CCP161,87,2004
STURMXX	Sturmian bound-State and scattering	source	manual
EFADDY	Faddeev bound state	source	manual
TWOFNR	Finite-range DWBA direct reactions to second order	source	manual
TWOFNR11	Shortened version of TWOFNR for one step	source front-end	manual

wspot	Woods Saxon code for bound states and decay widths	source	manual
RADCAP	Potential model for direct capture reactions	source	manual
Dweiko	Nuclear scattering at intermediate energies	source	manual
MOMDIS	Glauber model for knockout reactions	source	manual
EMPIRE-3.1	Modular system of various reaction codes	source	NDS108,2655,2007
DW81	A DWBA code for nucleus-nucleus scattering	source	manual
DW91	A code for microscopic analysis of nucleon-nucleus scattering	source	manual
DWBA91	Inelastic scattering of nucleons with particle-hole final state	source	manual
DWBA98	Inelastic scattering of nucleons with particle-hole final state	source	manual
ECIS	A general DWBA program	source	manual
CHUCK3	Coupled channels, Born approximation, zero range code (readme)	source library	manual inputs
DWUCK4	Distorted wave, Born approximation, zero range code (readme)	source library	manual inputs
DWUCK5	Distorted wave, Born approximation, finite range code (readme)	source library	manual inputs
CCFULL	Coupled channels for heavy-ion fusion reactions	source	CPC123.143,1999 inputs outputs

Fresco – Ian Thompson

j2.in
C:/aw/0000/fresco/sdpfm/

Page 2/2
Last modification: 10/9/2011 11:31:06 PM

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&POT kp=6 at= 30.000 rc=1.25  / #neutron bound state potential
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&POT kp=9 type=1 p1=  91.23 p2=   1.17 p3=   0.71 p4=   0.01 p5=   1.33 p6=   0.72 /
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PSPad editor 4.5.4 (2265) | www.pspad.com 10/10/2011 11:06:19 PM brown

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&Overlap kn1= 7 ic1=3  ic2=1  in=2  kind=0 nn= 1 l= 3 sn=0.5 j= 3.50 kbpot=6 be=
3.638 isc=1 ipc=0 /
&Overlap kn1= 9 ic1=3  ic2=1  in=2  kind=0 nn= 2 l= 1 sn=0.5 j= 1.50 kbpot=6 be=
3.638 isc=1 ipc=0 /

&Overlap kn1=200 kn2=270 ic1=2 ic2=1 in=2 kind=6 nn= 5 l=0 lmax=0
          sn=0.0 ia=1 j= 2.0 ib=1
          kbpot=1 be=0.1000  isc=0 ipc=2 /
&twont
          tnt(1, 1)= 5 tnt(2, 1)= 5 coef( 1)=  0.0393
          tnt(1, 2)= 5 tnt(2, 2)= 6 coef( 2)=  0.0080
          tnt(1, 3)= 7 tnt(2, 3)= 7 coef( 3)= -0.4297
          tnt(1, 4)= 7 tnt(2, 4)= 9 coef( 4)= -0.3258
          tnt(1, 5)= 9 tnt(2, 5)= 9 coef( 5)= -0.1225
      /
&overlap /

&Coupling icto=2 icfrom=1 kind=7 ip1=0 ip2=1 ip3=5/
&CFP in=1 ib=1 ia=1 kn=30 a=1.00  /
&CFP in=-2 ib=1 ia=1 kn=200 a=1.00  /
&COUPLING icto= 3 icfrom= 1 kind=7 ip1= 1 ip2= 1 ip3= 0  p1= -163.2 / # transfer (t,
d)
  &cfp  in= 1 ib=  1 ia=  1 kn=  1 a=   1.176  /
  &cfp  in= 2 ib=  1 ia=  1 kn=  5 a=   0.7071 /
  &cfp  in= 2 ib=  2 ia=  1 kn=  6 a=   0.7071 /
  &cfp  in= 2 ib=  3 ia=  1 kn=  7 a=   0.7071 /
  &cfp  in= 2 ib=  4 ia=  1 kn=  9 a=   0.7071 /
  &cfp /
&COUPLING icto= 2 icfrom= 3 kind=7 ip1= 0 ip2= 1 ip3= 0  p1= -122.5 / # transfer (d,
p)
  &cfp  in= 1 ib=  1 ia=  1 kn=  2 a=   1.000   /
  &cfp  in= 2 ib=  1 ia=  1 kn=  5 a=   0.0393  /
  &cfp  in= 2 ib=  1 ia=  1 kn=  6 a=   0.0080  /
  &cfp  in= 2 ib=  1 ia=  3 kn=  7 a=  -0.4297  /
  &cfp  in= 2 ib=  1 ia=  3 kn=  9 a=  -0.3258  /
  &cfp  in= 2 ib=  1 ia=  4 kn=  9 a=  -0.1225  /
  &cfp /
&coupling /
```

PSPad editor 4.5.4 (2265) | www.pspad.com 10/10/2011 11:06:19 PM brown

NSCL

j0.dal
c:\asl\fresco\pfcs40\

Page:1/1
Last modification: 12/8/2011 4:36:34 PM

```
1: bbcm00_cc00.tma
2: re = pt
3: el = 35.
```

PRPad editor 4.5.4 (2006) www.pepad.com

8/11/2012 10:43:52 AM

Brown

j0.dai
c:\aa\fresco\pt\ca40\

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2: re = pt
3: el = 35.
```
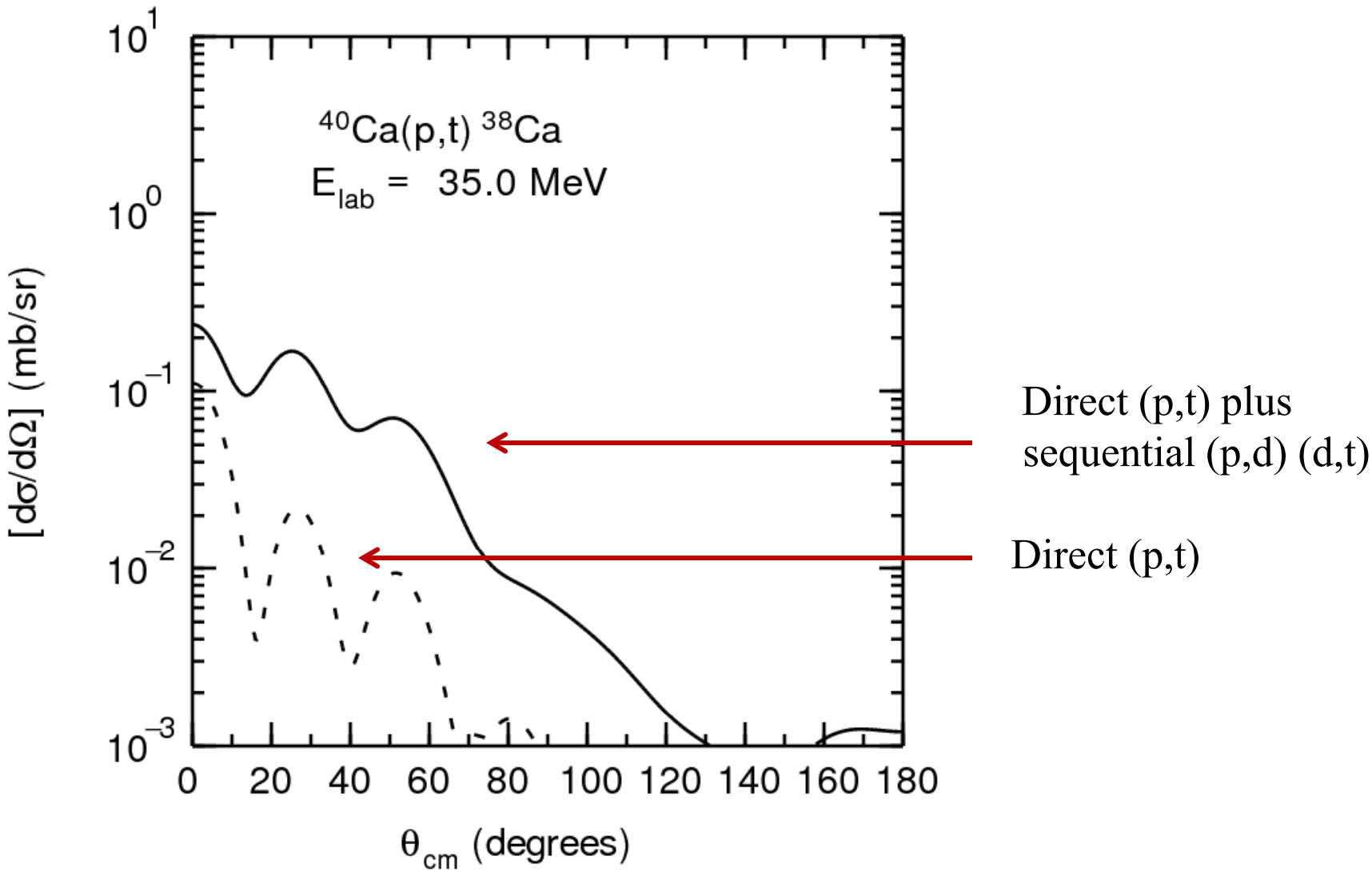


^{40}Ca(p,t) ^{38}Ca
E_{lab} = 35.0 MeV
[dσ/dΩ] (mb/sr)
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
0 20 40 60 80 100 120 140 160 180
θ_{cm} (degrees)
Direct (p,t) plus
sequential (p,d) (d,t)
Direct (p,t)

TNA (two-nucleon overlap amplitudes) contain all of the nuclear structure input.

The program fr2in contains the mass table and a sets of global optical potentials some of which are used as “defaults”

For the bound states we take Woods-Saxon potential with the well-depth adjusted to half of the two-nucleon separation energy.

Finte-range DWBA

Table 1: Light particle properties (finite size)

nucleus	J	configuration	
t, ^{3}He	1/2	$(0s)^3$	
d	0	$(0s)^2$	unbound state - not included
d	1	$(0s)^2$	bound state - included
p, n	1/2	$(0s)^1$	

Table 2: Light particle spectroscopic amplitudes

reaction	J_i	J_f	amplitude	operator
(t,p)	1/2	1/2	1.000	(nn) $\Delta S = 0$
(t,d)	1/2	1	1.176	(n) $\Delta S = 1/2$
(d,p)	1	1/2	1.000	(n) $\Delta S = 1/2$
(^{3}He,p)	1/2	1/2	1.176	(np) $\Delta S = 1$
(^{3}He,d)	1/2	1	1.176	(p) $\Delta S = 1/2$
(d,p)	1	1/2	1.000	(n) $\Delta S = 1/2$

NSCL

```
proton potentials
 [BG] Bechetti-Greenlees (A>40 20<E<50 MeV):     Phys Rev 182, 1190 (1969)
*[CH] Chapel-Hill 89 Global set (A>40 E>10 MeV):Phys Rep 201, 57 (1991)
 [ME] Menet (30<E<60):                           ADNTD 17, 6 (1976)
 [PE] Perey (E<20MeV):                           ADNTD 17, 6 (1976)

deuteron potentials
 [LH] Lohr-Haeberli (A>40 8<E<13 MeV):           ADNTD 17, 6 (1976)
 [PP] Perey-Perey (12<E<25 MeV) no spin-orbit:   ADNTD 17, 6 (1976)
*[DG] Daehnick Global (A>27 12<E<90 MeV)         PRC 21, 2253 (1980)

triton potentials
 [BG] Bechetti-Greenlees:                        ADNTD 17, 6 (1976)
*[XL] X. Li et al Global potential < 40 MeV:     NPA 789, 103 (2007)
 [PA] D.Y. Pang et al. GDP08                     PRC 79, 024615 (2009)

helium potentials
*[BG] Bechetti-Greenlees:                        ADNTD 17, 6 (1976)
 [PA] D.Y. Pang et al. GDP08                     PRC 79, 024615 (2009)
```

Thanks to Jeff Tostevin for these subroutines

Two-nucleon spectroscopic amplitudes

$$\mathrm{TNA}(f,i,a,b) = \frac{<(A)J_f||[a_a^+ a_b^+]^\lambda||(A-2)J_i>}{\sqrt{(1+\delta_{ab})}}$$

$$= \sum_m (-1)^{J_i+J_f+\lambda}\sqrt{2\lambda+1}\left\{\begin{array}{ccc} J_f & J_i & \lambda \\ j_a & j_b & J_m \end{array}\right\} \times$$

$$\frac{<(A)J_f||a_a^+||(A-1)J_m><(A-1)J_m||a_b^+||(A-2)J_i>}{\sqrt{(1+\delta_{ab})}}$$

When $J_i = 0$, then $\lambda = J_f$, $J_m = j_b$ and assume one intermediate state for each j_b:

$$\mathrm{TNA}(f,i,a,b) = \frac{<(A)J_f||a_a^+||(A-1)j_b><(A-1)j_b||a_b^+||(A-2)J_i=0>}{\sqrt{(1+\delta_{ab})}}$$

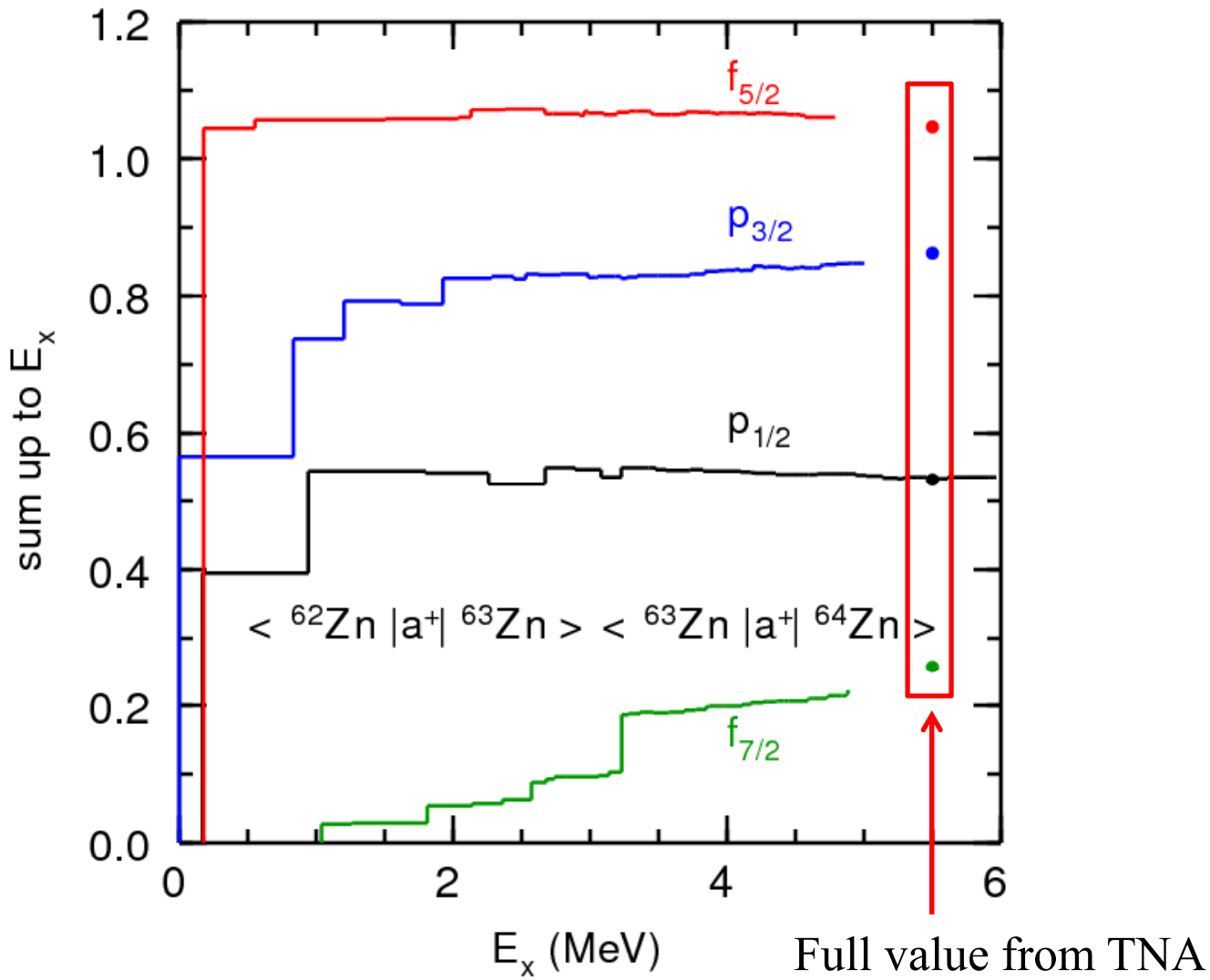
$$= \frac{\mathrm{ONA}(f,m=b,a)\ \ \mathrm{ONA}(m=b,i,b)}{\sqrt{(1+\delta_{ab})}}$$

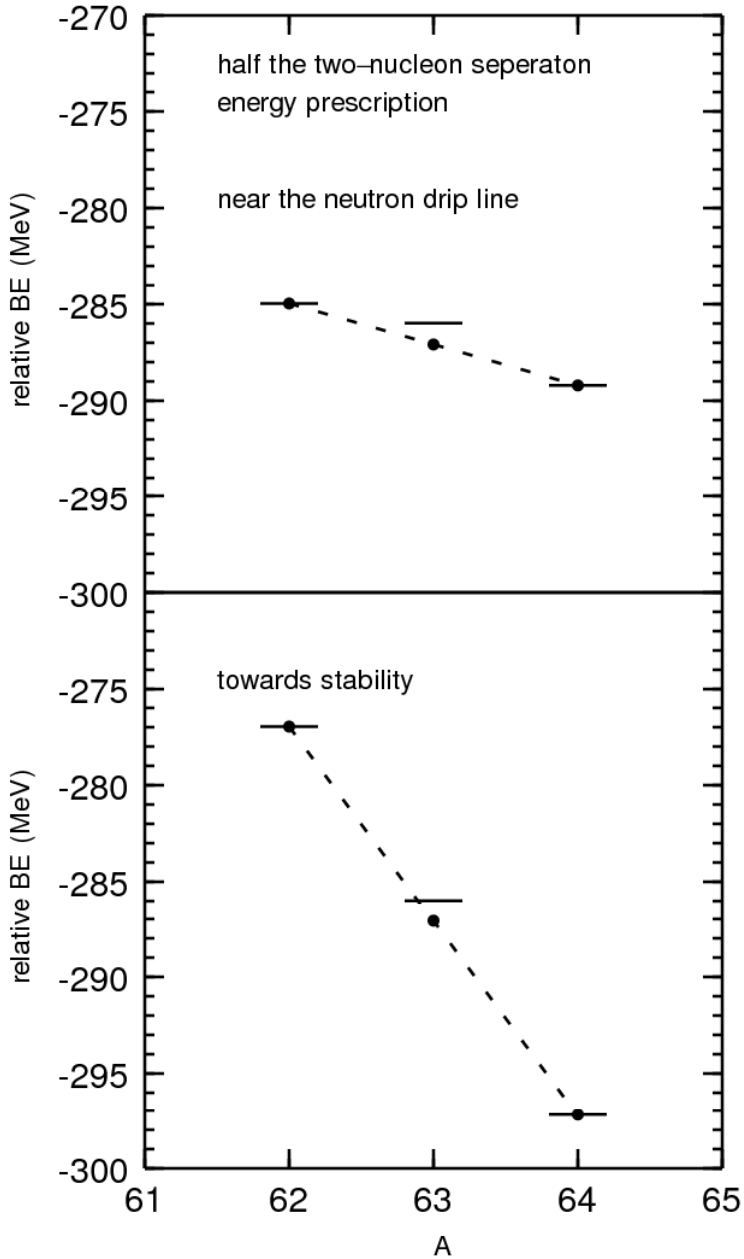
So for the one-nucleon spectroscpic amplitudes (ONA) we can take, for example

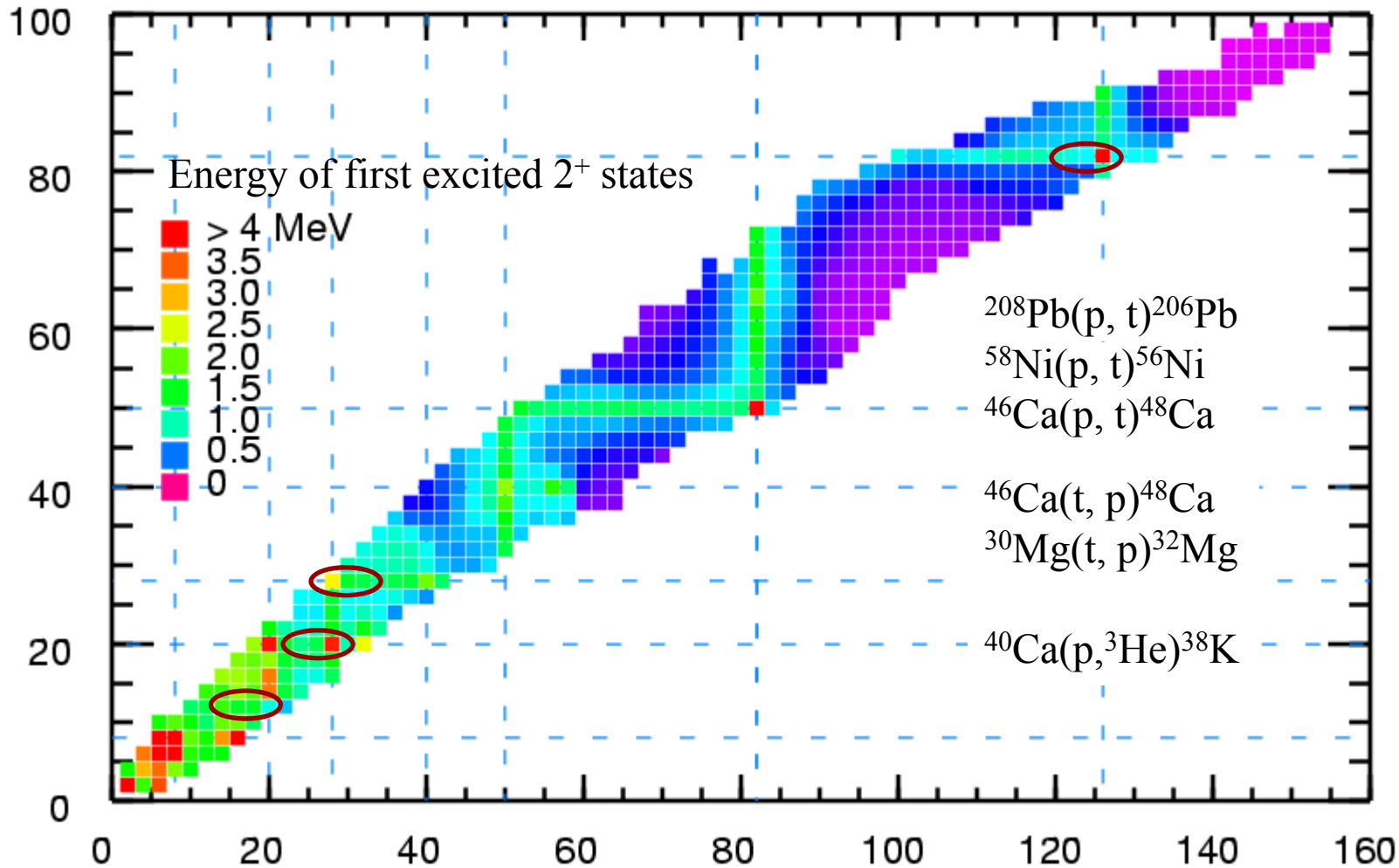
$$\mathrm{ONA}(f,m=b,a) = \mathrm{TNA}(f,i,a,b)$$

$$\mathrm{ONA}(m=b,i,b) = \sqrt{(1+\delta_{ab})}$$

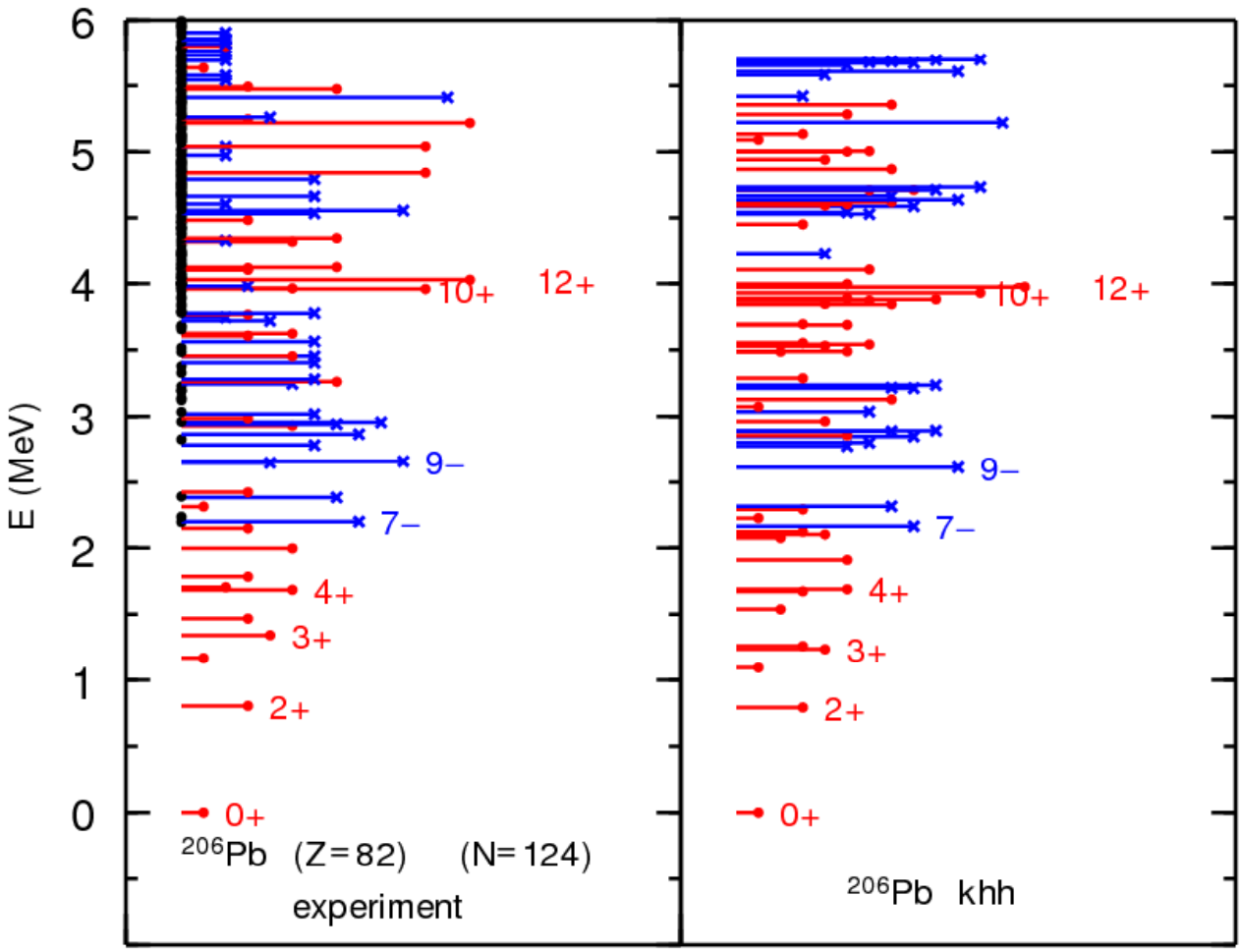
Example of the intermediate states $^{64}Zn(p,t)^{62}Zn$




half the two–nucleon seperaton
energy prescription
near the neutron drip line
towards stability
relative BE (MeV)
relative BE (MeV)
-270
-275
-280
-285
-290
-295
-300
-275
-280
-285
-290
-295
-300
61
62
63
64
65
A


Energy of first excited 2+ states
> 4 MeV
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
208Pb(p, t)206Pb
58Ni(p, t)56Ni
46Ca(p, t)48Ca
46Ca(t, p)48Ca
30Mg(t, p)32Mg
40Ca(p,3He)38K
0
20
40
60
80
100
120
140
160

NSCL


E (MeV)
6
5
4
3
2
1
0
12+
10+
9−
7−
4+
3+
2+
0+
206Pb (Z=82) (N=124)
experiment
206Pb khh

PHYSICAL REVIEW C VOLUME 14, NUMBER 2 AUGUST 1976

Finite-range evaluation of (p-d, d-t) with momentum space techniques*

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and Lawrence Berkeley Laboratory, Nuclear Science Division, University of California, Berkeley, California 94720

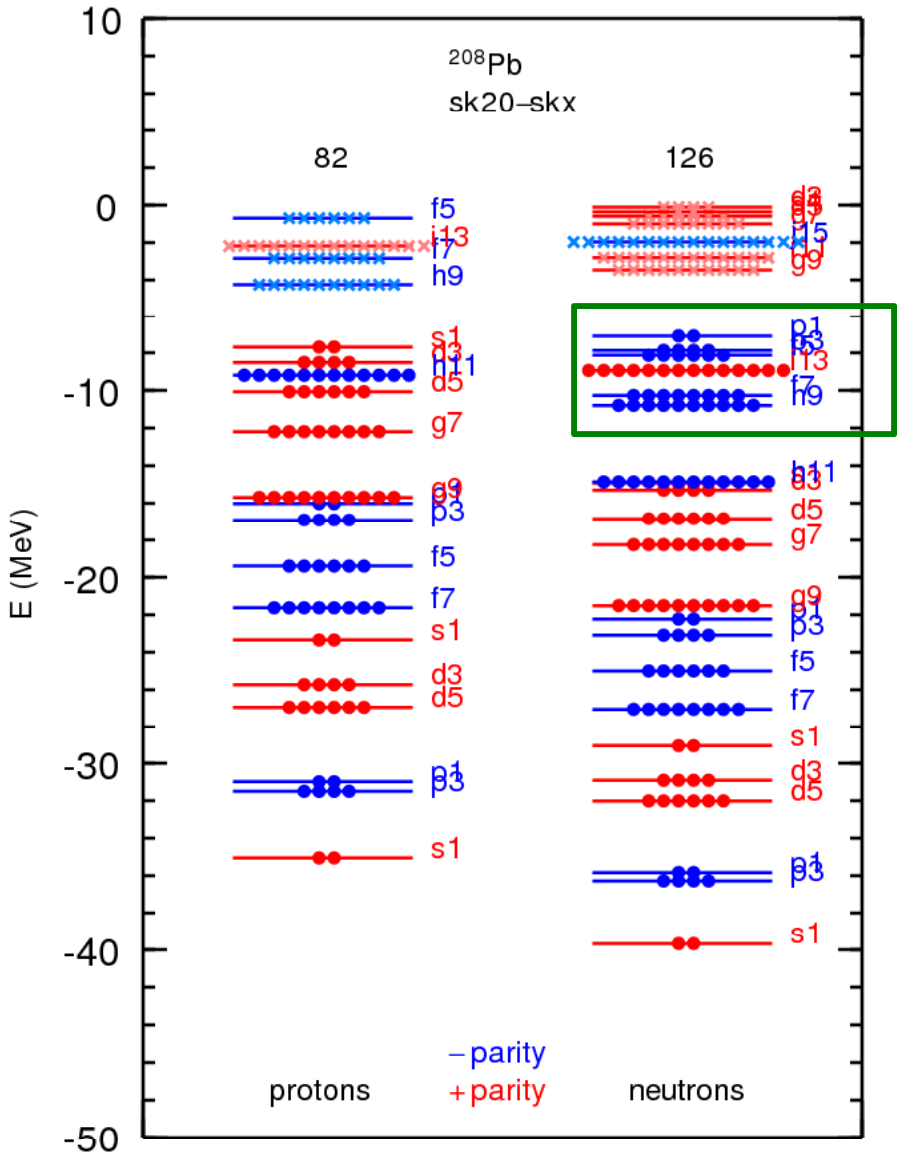
(Received 26 February 1976)

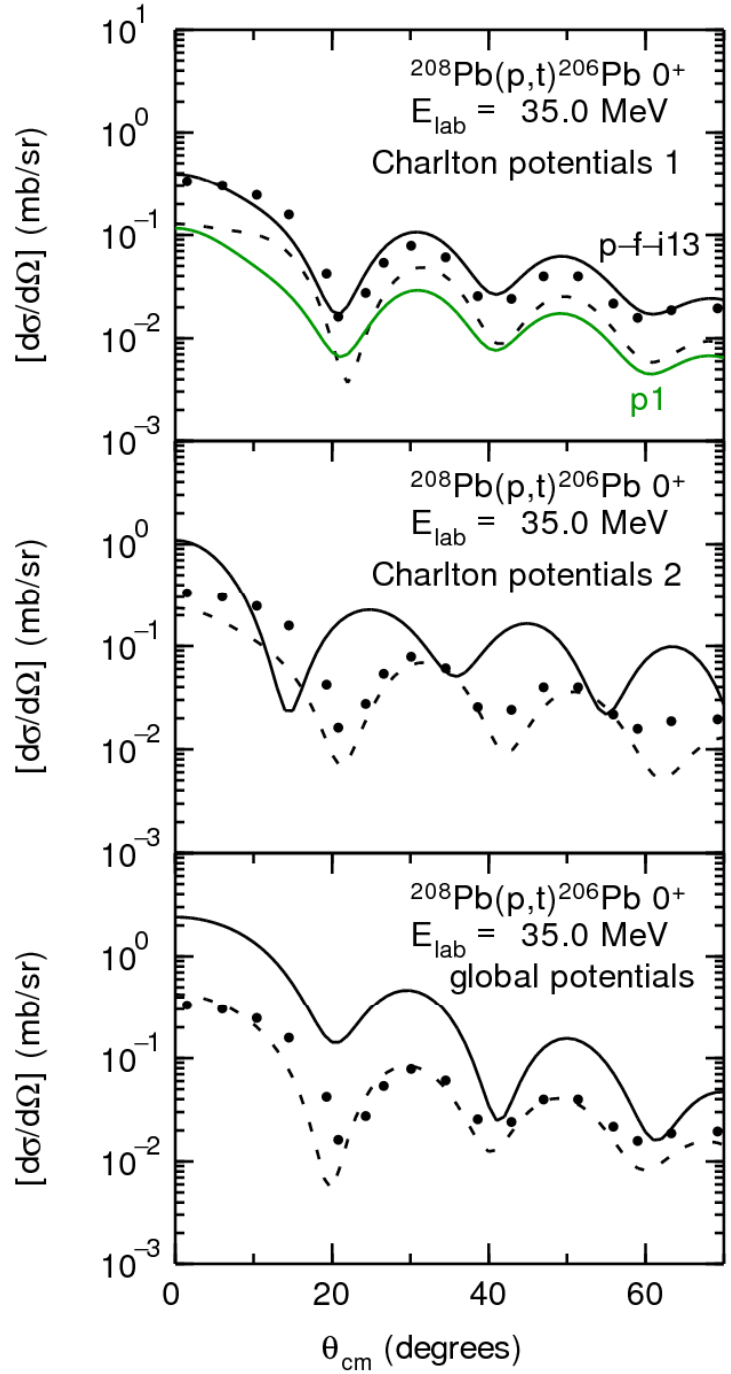
A momentum space methodology is presented for calculating second order distorted wave Born approximation matrix elements without the use of the zero-range approximation. This methodology is applied to the sequential transfer term in (p,t) reactions. Examples are presented for ^{208}Pb$(p,t)^{206}$Pb which show that: (1) finite-range effects can be large, (2) the shape of the calculated differential cross section can be strongly dependent on the contribution from a sequential transfer mechanism, and (3) the post-prior interchange usually used is probably the best realistic approximation.

L. A. CHARLTON

TABLE I. Optical parameters.

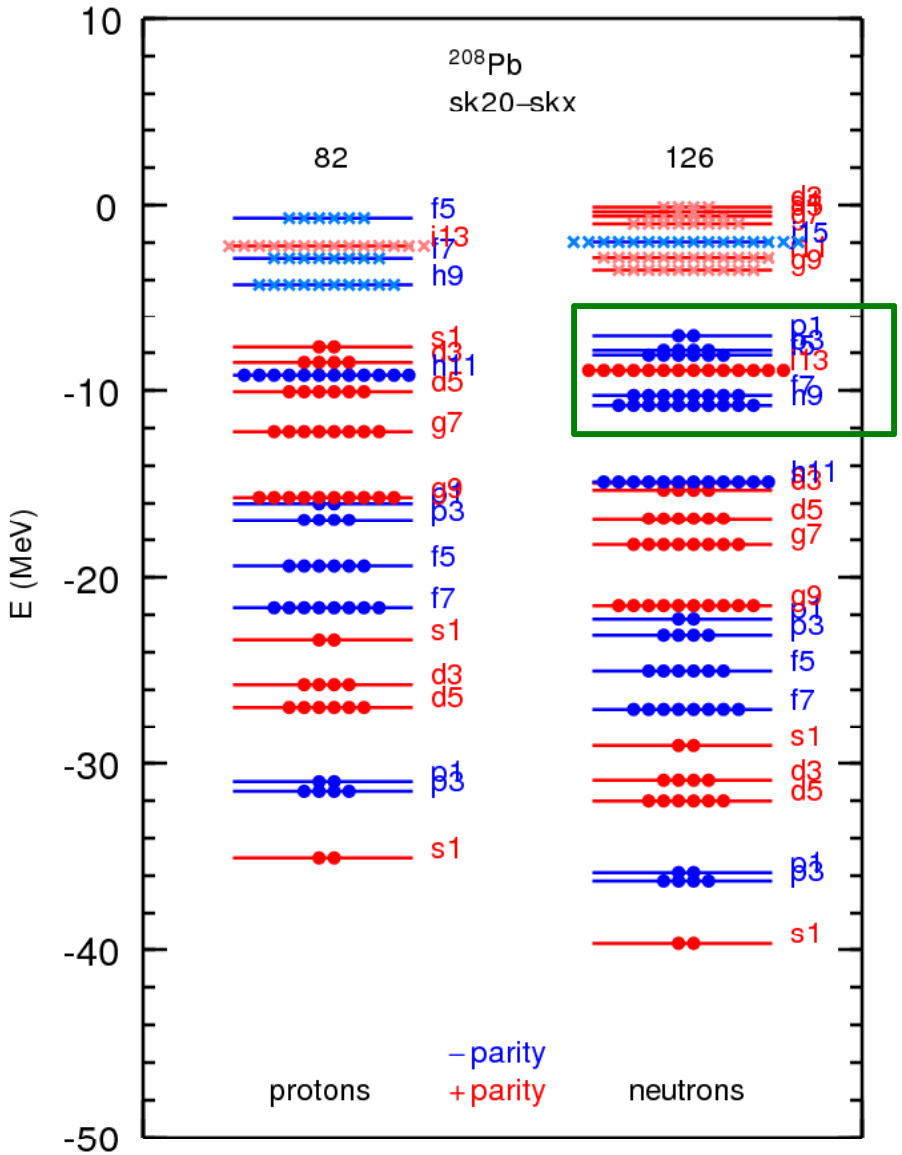
Set	Channel	V	W	W_D	r_c	r_v	a_v	r_w	a_w	Reference
1	p	47.9	0	10.0	1.25	1.25	0.65	1.25	0.76	17
	d	97.8	0	14.0	1.25	1.25	0.68	1.25	0.78	17
	t	149.8	12.0	0	1.24	1.24	0.68	1.43	0.87	18
2	p	53.4	5.0	5.6	1.17	1.17	0.75	1.32	0.66	19
	d	103.9	1.2	1.2	1.17	1.17	0.75	1.32	0.66	2
	t	167.0	10.0	0	1.16	1.16	0.75	1.50	0.82	18


^{208}Pb
sk20–skx
82
126
E (MeV)
10
0
-10
-20
-30
-40
-50
f5
i13
f7
h9
s1
d3
h11
d5
g7
g9
p3
f5
f7
s1
d3
d5
p1
p3
s1
p1
p3
i13
f7
h9
h11
d3
d5
g7
g9
p3
f5
f7
s1
d3
d5
p1
p3
s1
protons
neutrons
– parity
+ parity

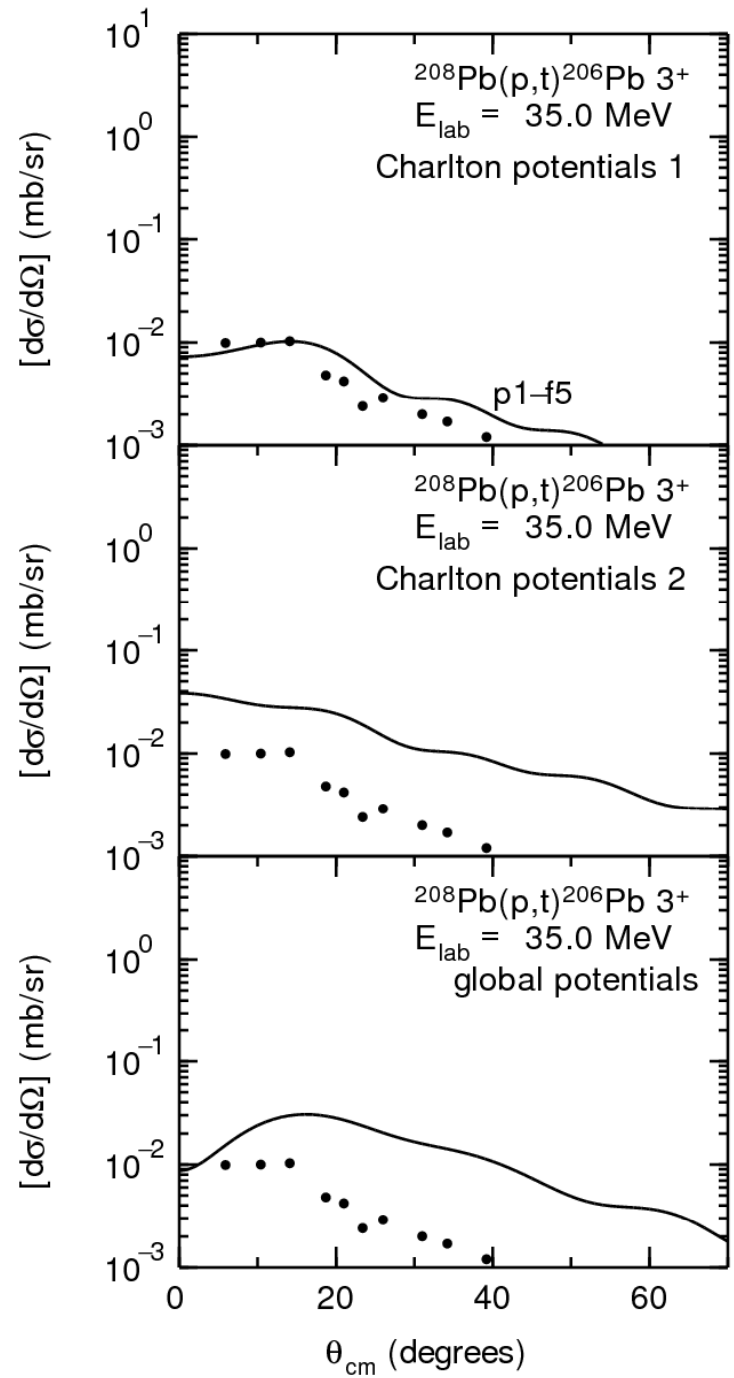

^{208}Pb(p,t)^{206}Pb 0$^+$
E_{lab} = 35.0 MeV
Charlton potentials 1
p–f–i13
p1
^{208}Pb(p,t)^{206}Pb 0$^+$
E_{lab} = 35.0 MeV
Charlton potentials 2
^{208}Pb(p,t)^{206}Pb 0$^+$
E_{lab} = 35.0 MeV
global potentials
[dσ/dΩ] (mb/sr)
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
0
20
40
60
θ_{cm} (degrees)

NSCL

2012



^{208}Pb
sk20–skx
82
126
E (MeV)
10
0
-10
-20
-30
-40
-50
f5
i13
f7
h9
s1
d3
h11
d5
g7
g9
p1
p3
f5
f7
s1
d3
d5
p1
p3
s1
p1
p3
f5
f7
h9
h11
d3
d5
g7
g9
p1
p3
f5
f7
s1
d3
d5
p1
p3
s1
protons
– parity
+ parity
neutrons



^{208}Pb(p,t)^{206}Pb 3$^+$
E_{lab} = 35.0 MeV
Charlton potentials 1
p1–f5
^{208}Pb(p,t)^{206}Pb 3$^+$
E_{lab} = 35.0 MeV
Charlton potentials 2
^{208}Pb(p,t)^{206}Pb 3$^+$
E_{lab} = 35.0 MeV
global potentials
[dσ/dΩ] (mb/sr)
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
0
20
40
60
θ_{cm} (degrees)

NSCL

^{58}Ni(p,t)^{56}Ni (near the proton drip line)

PHYSICAL REVIEW C VOLUME 10, NUMBER 5 NOVEMBER 1974

Levels of ^{56}Ni†

H. Nann* and W. Benenson

Cyclotron Laboratory and Department of Physics, Michigan State University, East Lansing, Michigan 48824

(Received 5 August 1974)

The ^{58}Ni(p, t)^{56}Ni reaction was studied at 40 and 45 MeV beam energy. An energy resolution of 10–25 keV permitted observation of 60 levels with excitation energy up to 10.5 MeV. Spin and parity are assigned to levels which were excited with characteristic angular distributions. These include 0^+ states at 3.95, 5.00, 6.44, 7.91, 9.92, 9.99, and 10.02 MeV.

NSCL

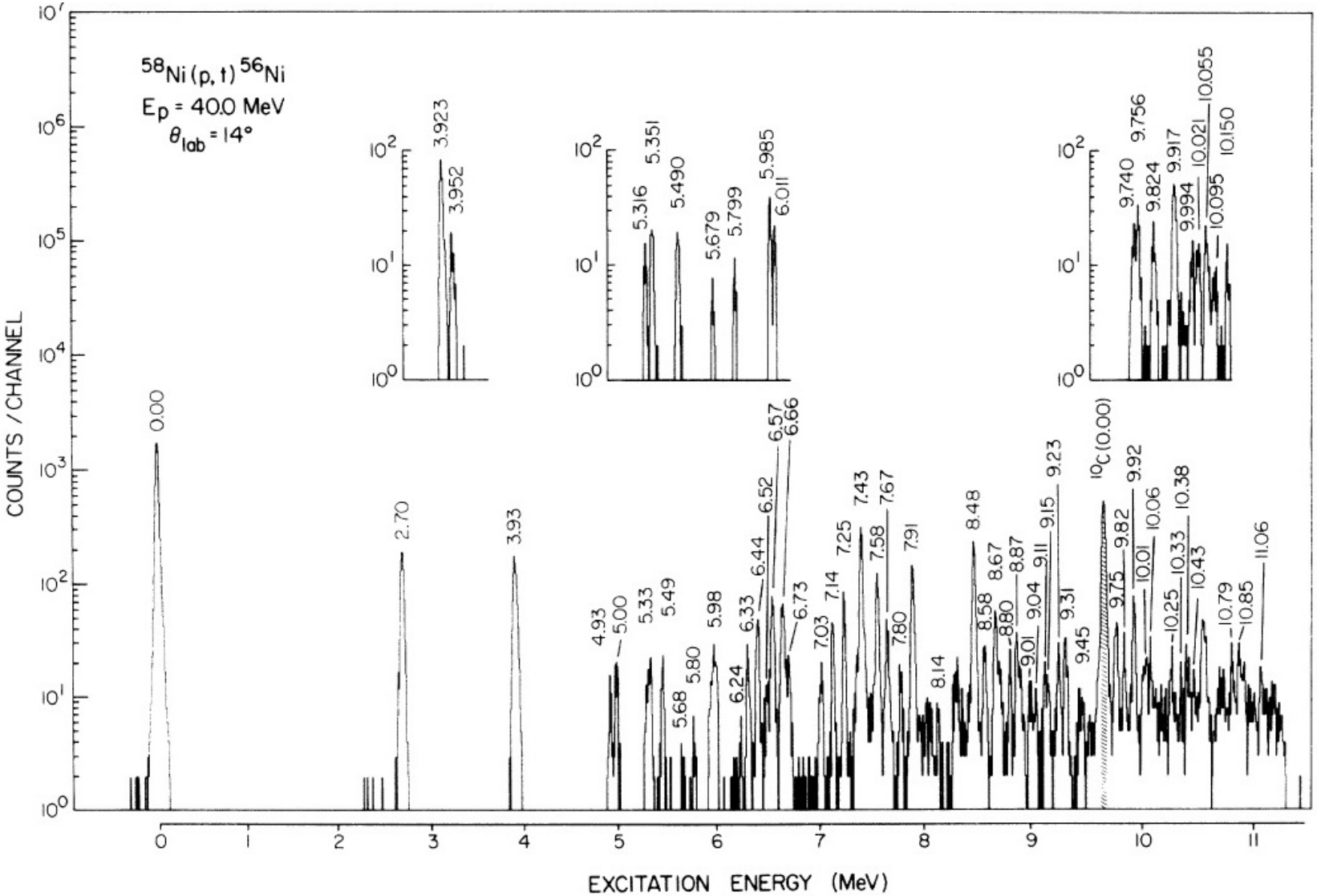


FIG. 1. Composite triton spectrum of the $^{58}Ni(p,t)^{56}Ni$ reaction at $\theta_{lab}=14°$.

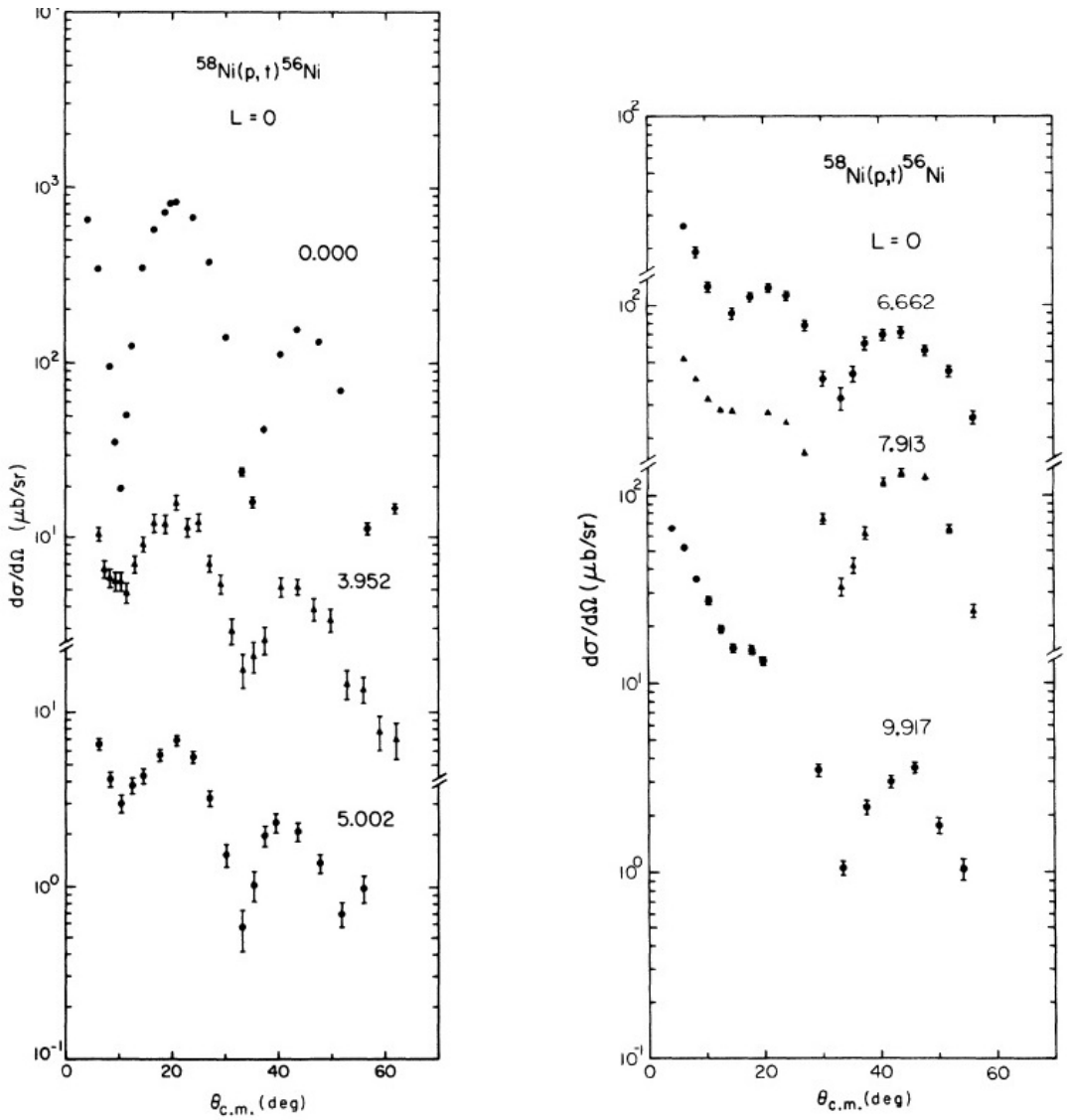
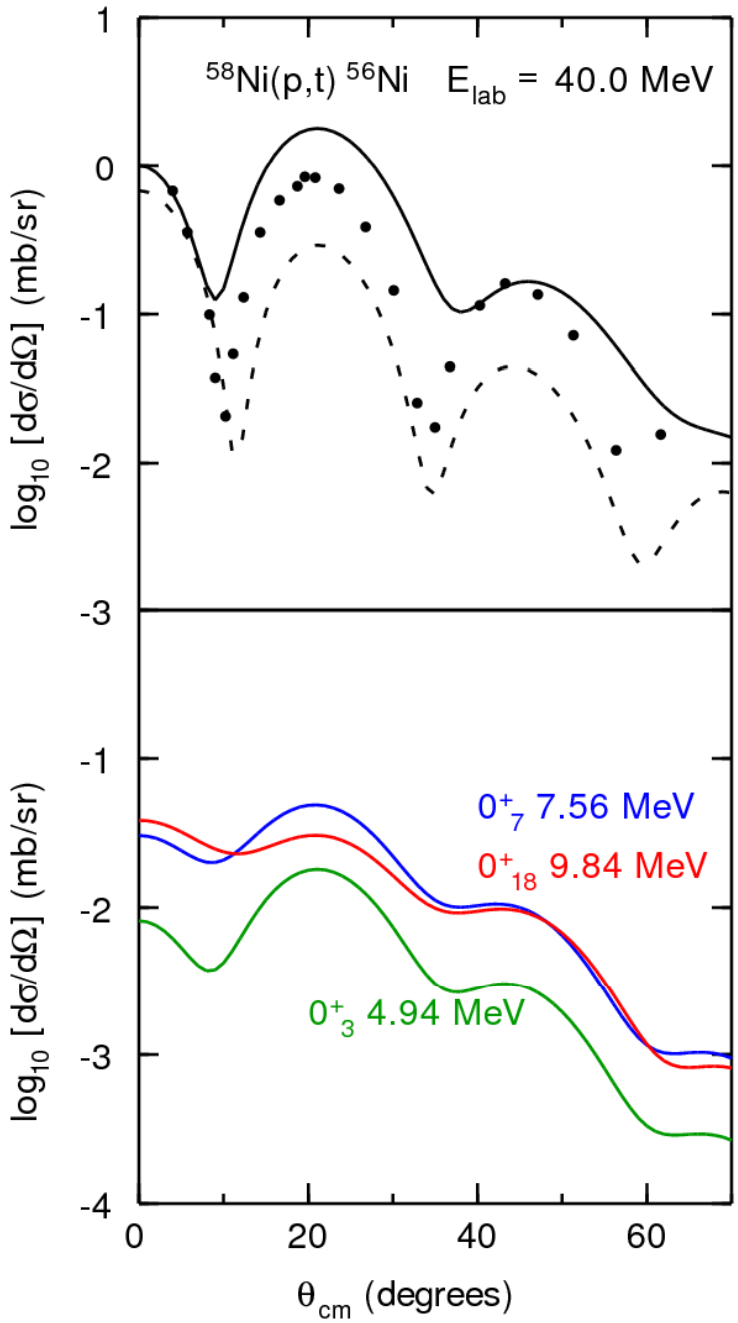
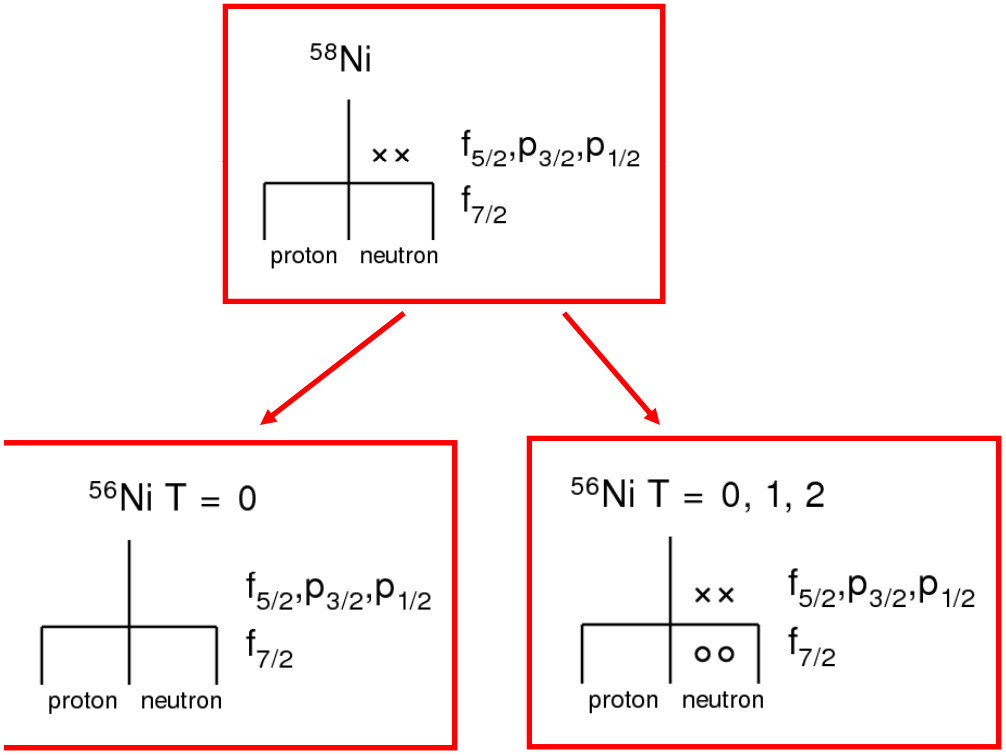


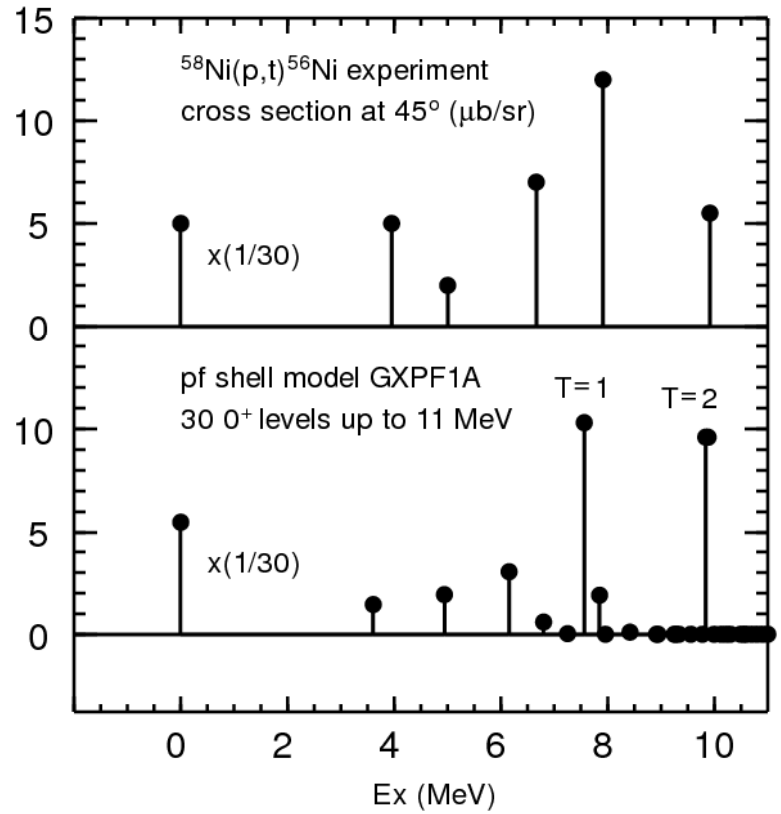
FIG. 2. (a), (b) Angular distributions for levels excited by $L=0$ transfers in the $^{58}Ni(p,t)^{56}Ni$ reaction.


^{58}Ni(p,t) ^{56}Ni E_{lab} = 40.0 MeV
$\log_{10}$ [dσ/dΩ] (mb/sr)
0^+_7 7.56 MeV
0^+_{18} 9.84 MeV
0^+_3 4.94 MeV
θ_{cm} (degrees)

$^{58}Ni(p,t)^{56}Ni$

Simplest shell model configurations





$^{46}Ca(p, t)^{48}Ca$

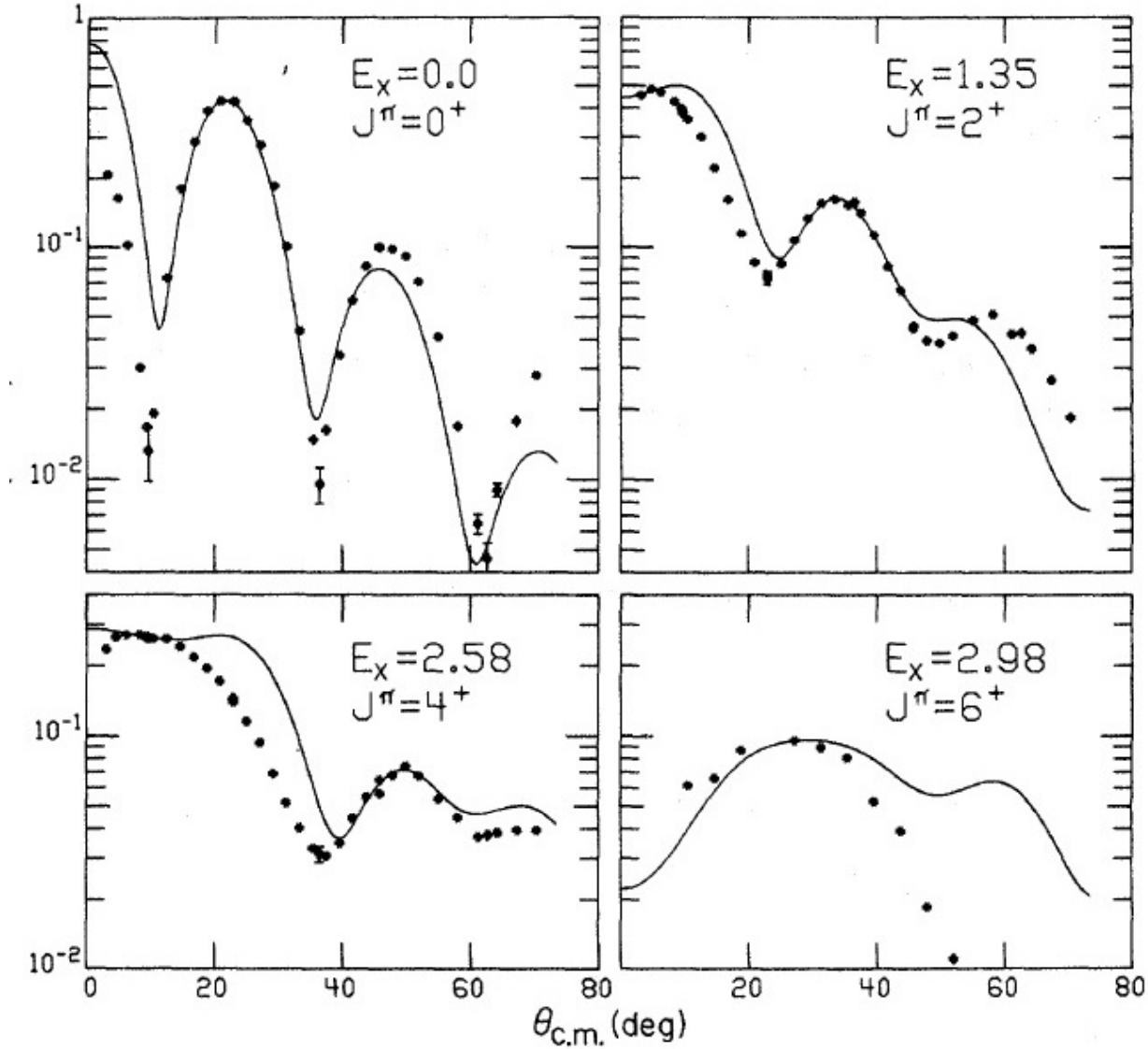
PHYSICAL REVIEW C VOLUME 8, NUMBER 2 AUGUST 1973

High-Resolution Study of $^{48}Ca(p,t)^{46}Ca$ at $E_p = 39$ MeV*

G. M. Crawley and P. S. Miller
Cyclotron Laboratory and Physics Department, Michigan State University, East Lansing, Michigan 48823

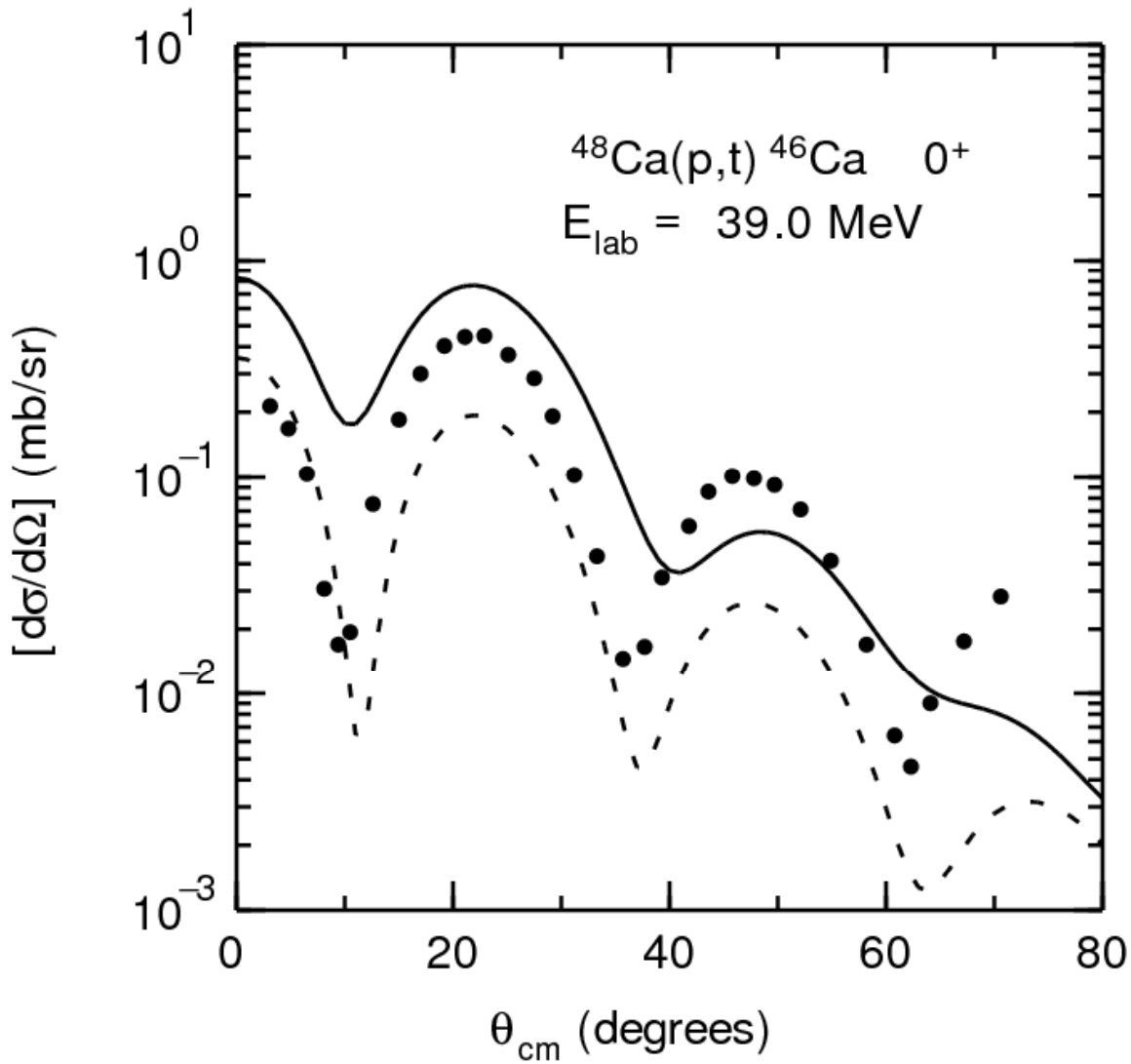
G. J. Igo and J. Kulleck
Physics Department, University of California, Los Angeles, California
(Received 22 December 1972)

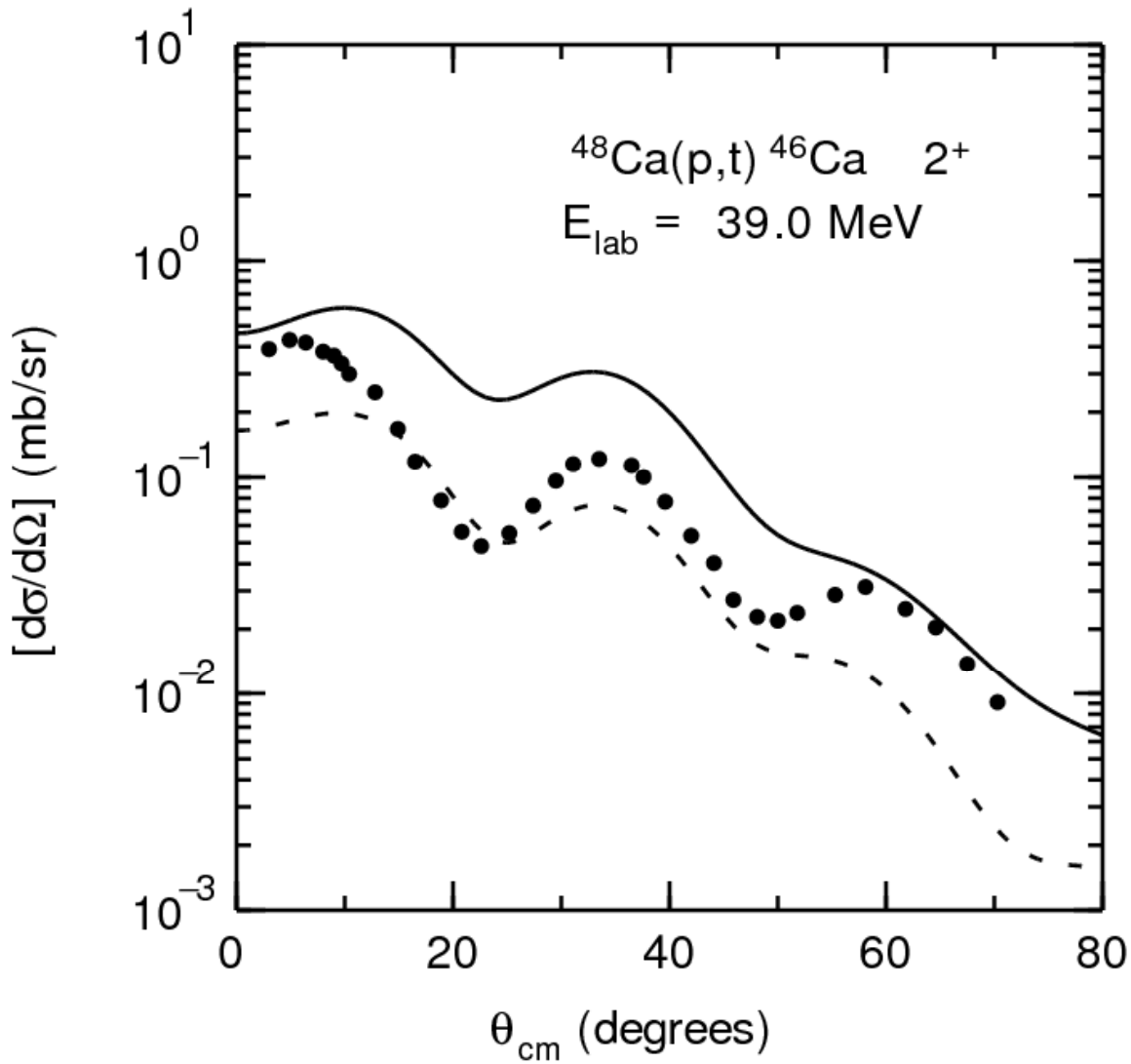
The ^{46}Ca nucleus was studied using the (p,t) reaction. A number of spin-parity assignments are clarified for the low-lying states. Many new energy levels are reported up to an excitation energy of 6.3 MeV including an additional 0^+ state at 4.76 MeV. Distorted-wave calculations with f-p shell wave functions give reasonable agreement for the first 0^+, 2^+, 4^+, and 6^+ states and for two weak 0^+ states near 5.5 MeV which were strongly excited in the $^{44}Ca(t,p)$ reaction.

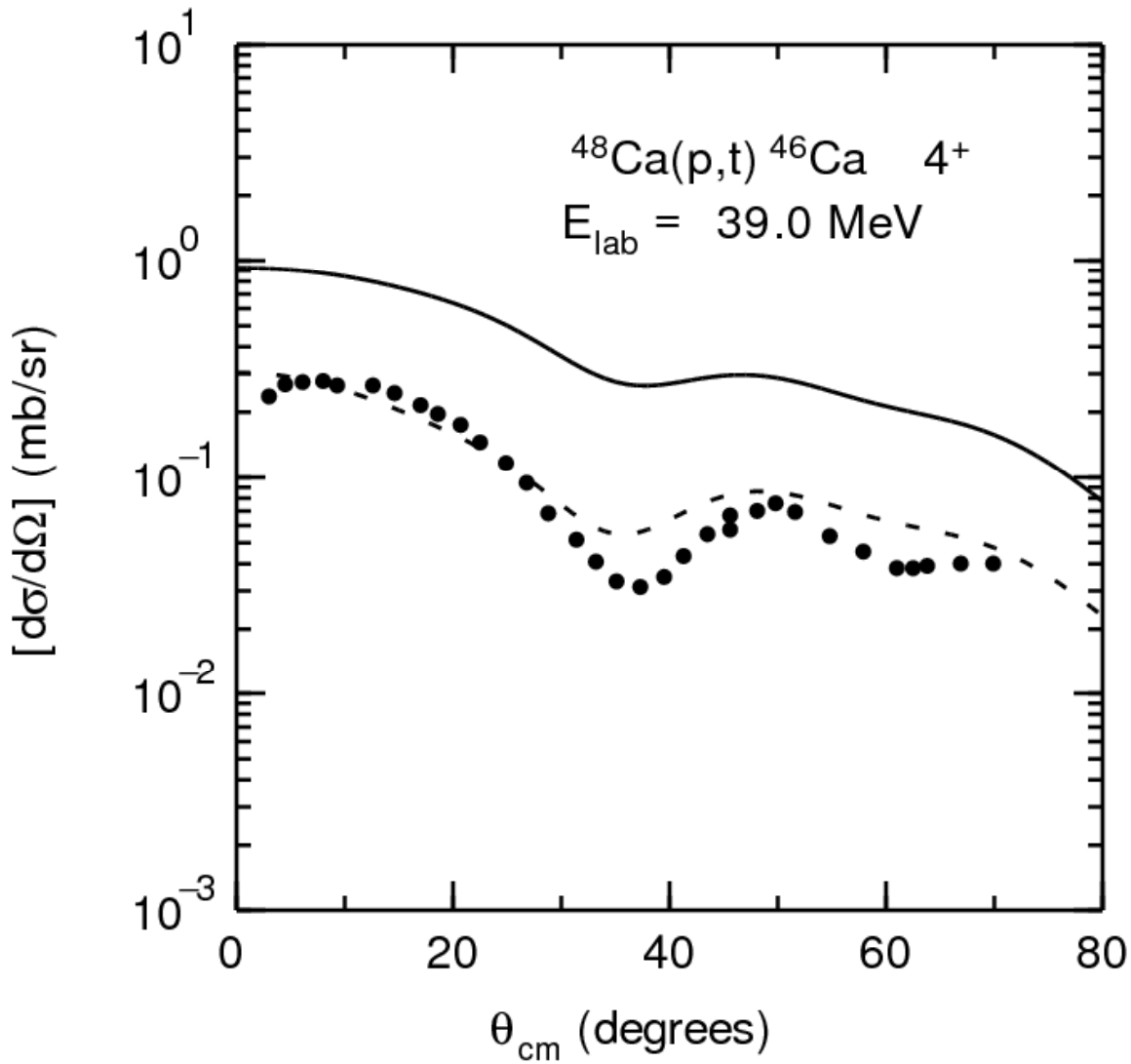

E_x=0.0
J^π=0$^+$
E_x=1.35
J^π=2$^+$
E_x=2.58
J^π=4$^+$
E_x=2.98
J^π=6$^+$
1
10^{-1}
10^{-2}
0
20
40
60
80
$\theta_{c.m.}$ (deg)

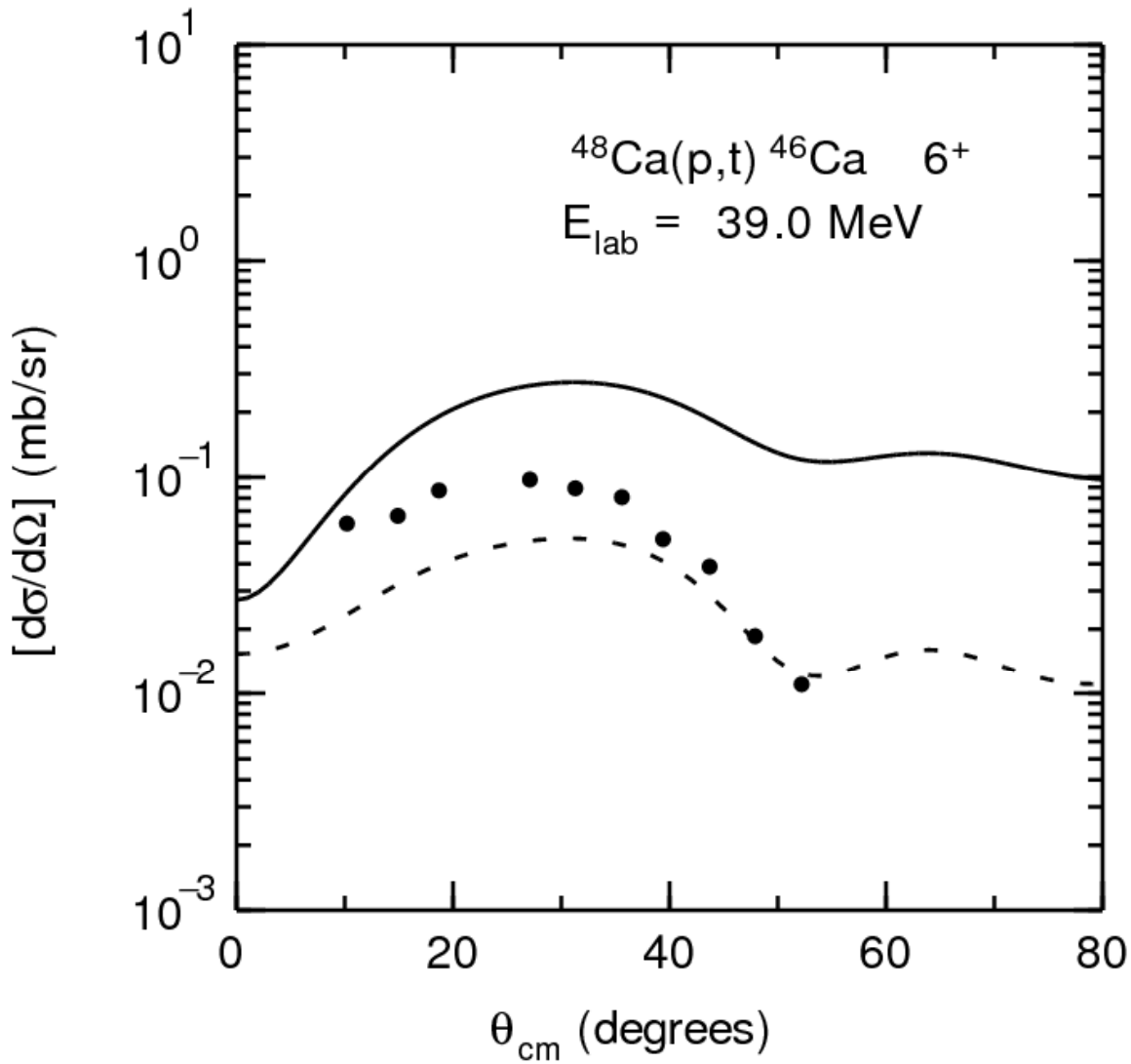
IV. DISTORTED-WAVE CALCULATIONS

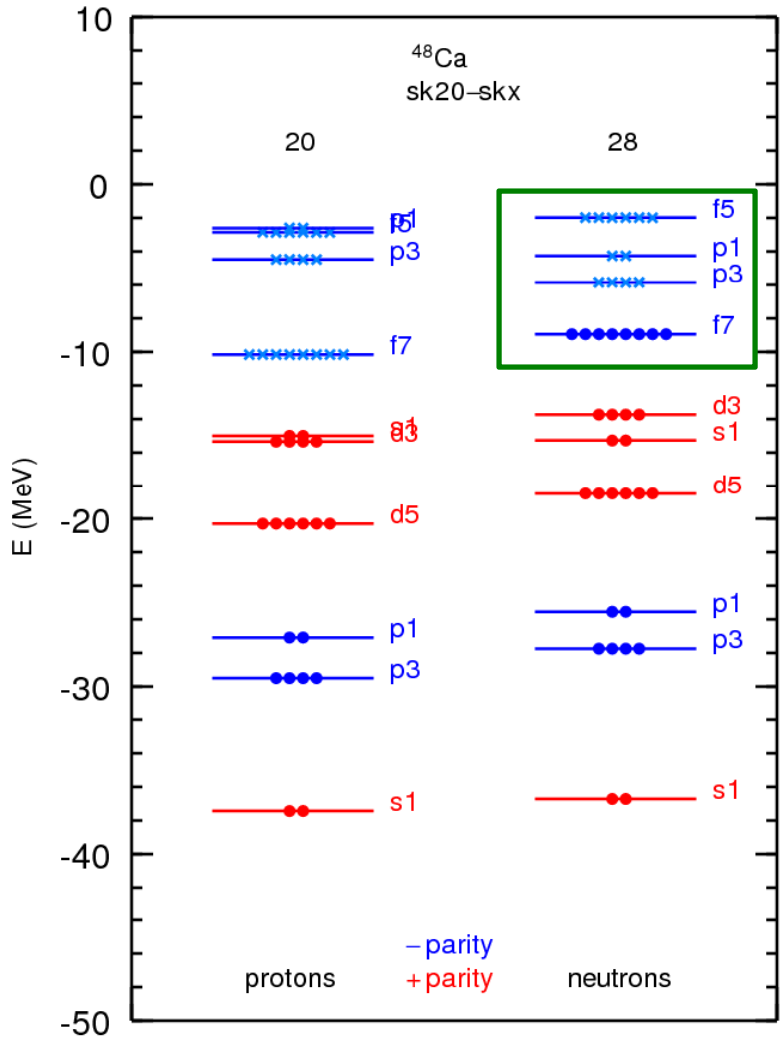
Distorted-wave calculations were carried out using the code DWUCK72.[14] Two different sets of proton parameters were used, one due to Becchetti and Greenlees[15] and the other due to Perey.[16] Almost 30 different sets of triton optical parameters, taken from a variety of sources,[2, 17-19] with real well depths ranging from 113 to 215 MeV were tried in an attempt to get a good fit to the low-lying states. The proton optical parameters and some of the more promising triton parameters are shown in Table II.

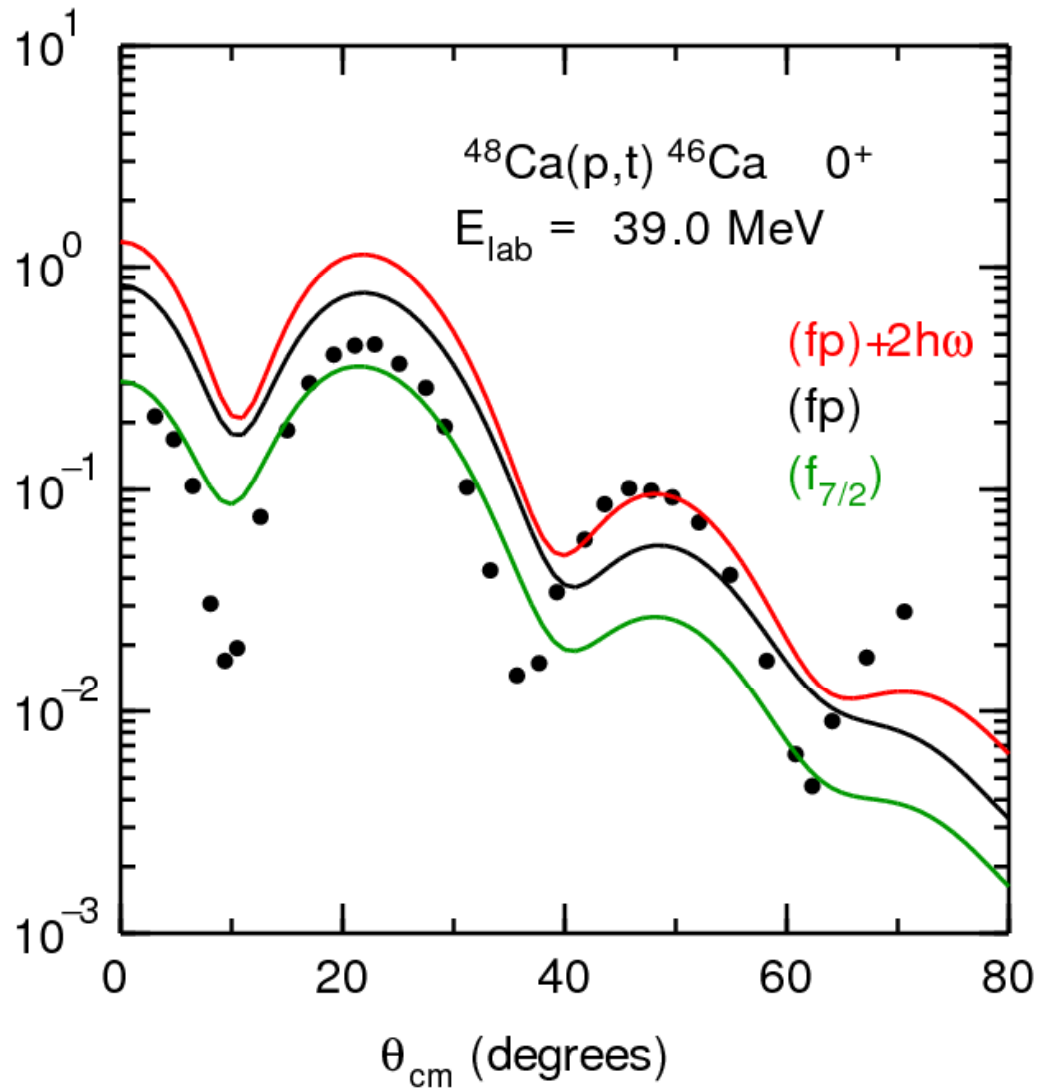

^{48}Ca(p,t) ^{46}Ca 0$^+$
E_{lab} = 39.0 MeV
[dσ/dΩ] (mb/sr)
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
0
20
40
60
80
θ_{cm} (degrees)


^{48}Ca(p,t) ^{46}Ca 2$^+$
E_{lab} = 39.0 MeV
[dσ/dΩ] (mb/sr)
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
0
20
40
60
80
θ_{cm} (degrees)


^{48}Ca(p,t) ^{46}Ca 4$^+$
E_{lab} = 39.0 MeV
[dσ/dΩ] (mb/sr)
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
0
20
40
60
80
θ_{cm} (degrees)


^{48}Ca(p,t) ^{46}Ca 6$^+$
E_{lab} = 39.0 MeV
[dσ/dΩ] (mb/sr)
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
0
20
40
60
80
θ_{cm} (degrees)


48Ca
sk20–skx
20
28
E (MeV)
10
0
-10
-20
-30
-40
-50
p1
p3
f7
s1
d3
d5
p1
p3
s1
f5
p1
p3
f7
d3
s1
d5
p1
p3
s1
protons
neutrons
– parity
+ parity


48Ca(p,t) 46Ca 0+
Elab = 39.0 MeV
(fp)+2hω
(fp)
(f7/2)
10^1
10^0
10^−1
10^−2
10^−3
0
20
40
60
80
θcm (degrees)

NSCL

The spectroscopic amplidute for di-proton decay ($k = 2$) is given by a coherent sum over matrix elements of a destruction operator for two nucleons coupled to $J = 0$ followed by an ls to jj transformation followed by a Moshinsky transformation:

$$S = \theta^2$$

$$\theta = \left(\frac{A}{A-k}\right)^{\lambda/2} \sum_{k\alpha,k\beta} < (A-k)\omega J || \frac{[\tilde{a}_{k_\alpha} \otimes \tilde{a}_{k_\beta}]^{J_o}}{\sqrt{(1+\delta_{k_\alpha k_\beta})}} || A\omega' J' >$$

TNA

$$\times < (\ell_\alpha, \ell_\beta, L); (s, s, S); J_o \mid (\ell_\alpha, s, j_\alpha); (\ell_\beta, s, j_\beta); J_o >$$

$$\times < (n_\alpha, \ell_\alpha); (n_\beta, \ell_\beta); L \mid (n, \ell); (N, \Lambda); L >$$

Cluster factors

where $k_\alpha = (n_\alpha, l_\alpha, j_\alpha)$.

In the Moshinsky transformation by energy conservation we have

$$\lambda = 2n_\alpha + \ell_\alpha + 2n_\beta + \ell_\beta = 2n + \ell + 2N + \Lambda$$

For di-proton decay $J_o = 0$, $L = 0$, $S = 0$, $n = 0$ and $l = 0$.

For the pf shell $\lambda = 6$ and $N = 3$.

NSCL

$^{46}Ca(t, p)^{48}Ca$

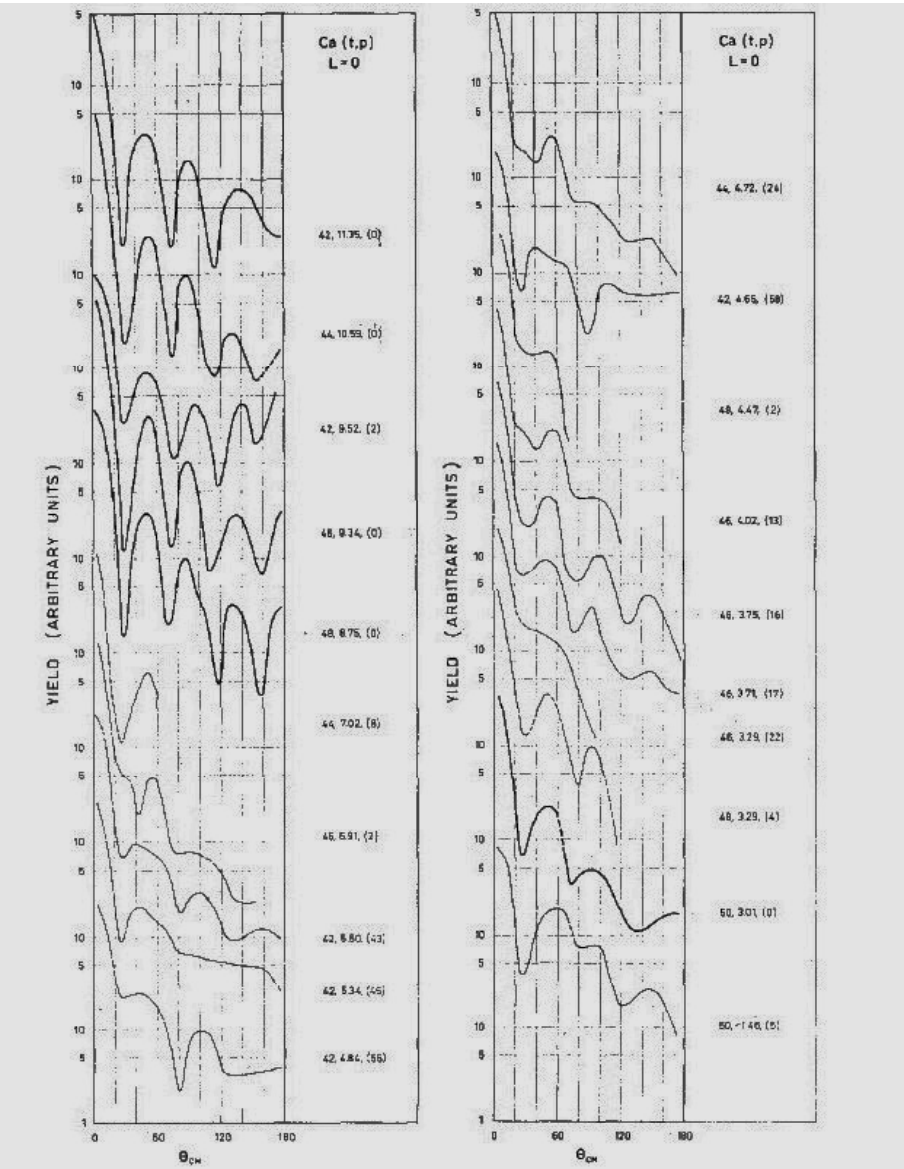
THE (t, p) REACTION WITH THE EVEN ISOTOPES OF Ca

J. H. BJERREGAARD, OLE HANSEN and O. NATHAN
The Niels Bohr Institute, University of Copenhagen, Denmark †

and

R. CHAPMAN, S. HINDS †† and R. MIDDLETON †††
AWRE, Aldermaston, Berkshire, England

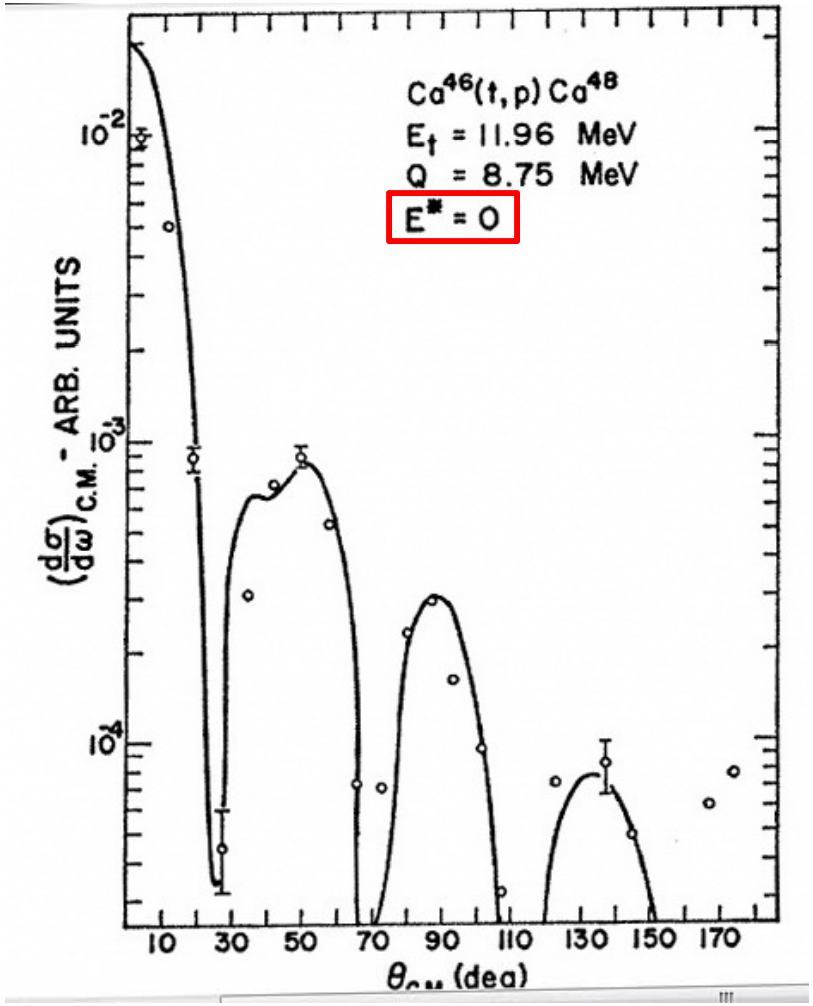
Received 7 July 1967

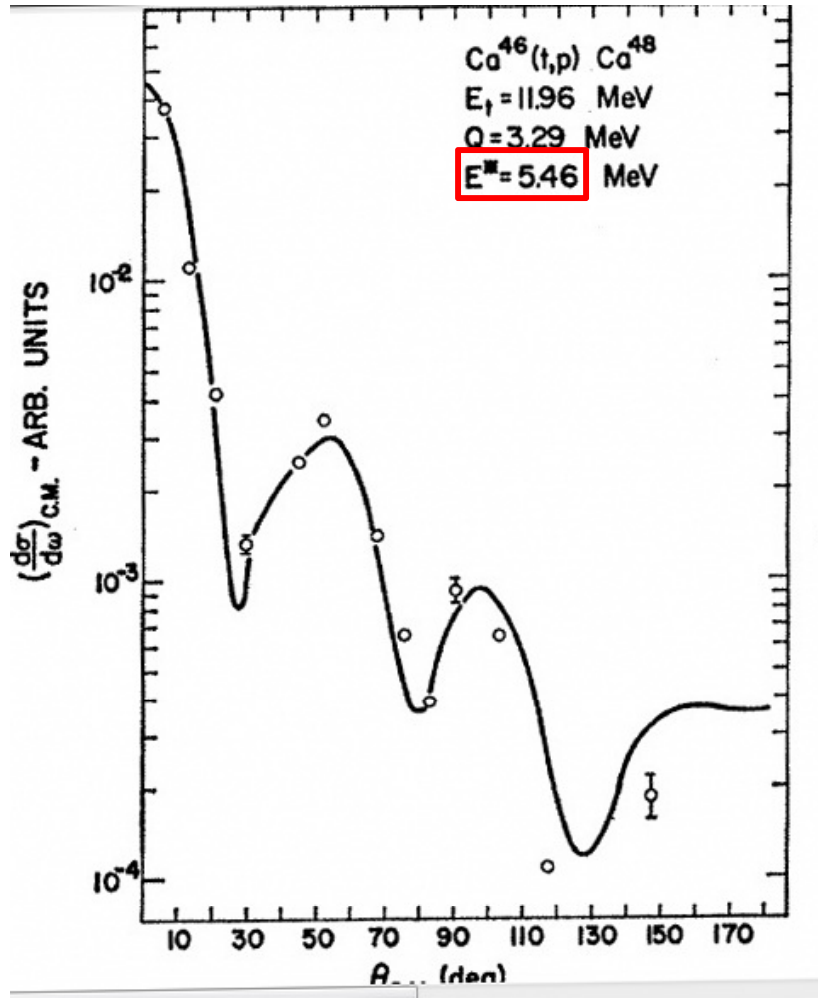

Ca (t,p)
L = 0
YIELD (ARBITRARY UNITS)
θCM
Ca (t,p)
L = 0
YIELD (ARBITRARY UNITS)
θCM

PHYSICAL REVIEW VOLUME 172, NUMBER 4 20 AUGUST 1968

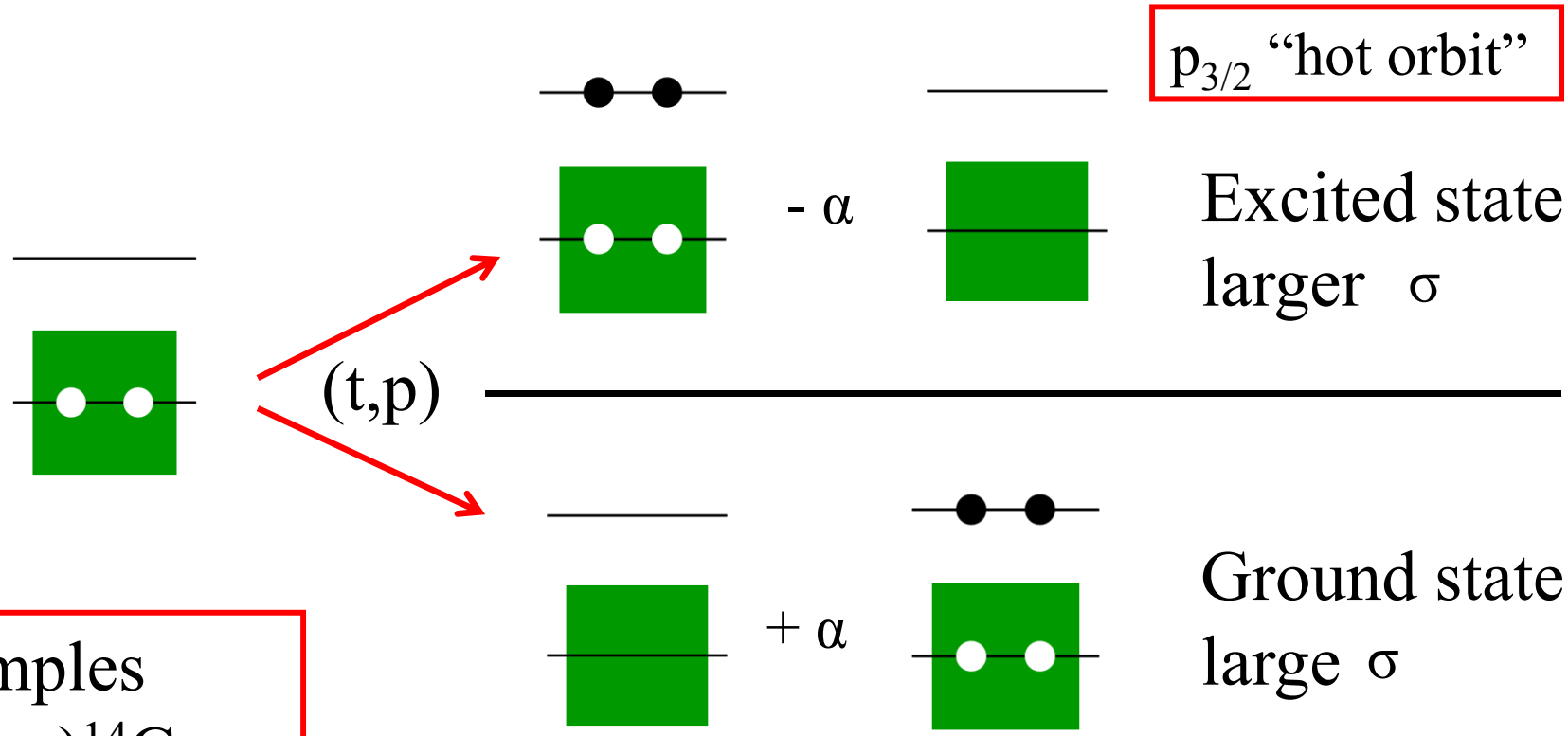
Analysis of Two-Neutron ($L=0$) Transfer Cross Sections for Calcium and Nickel*

B. F. Bayman and Norton M. Hintz
School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455
(Received 12 February 1968)

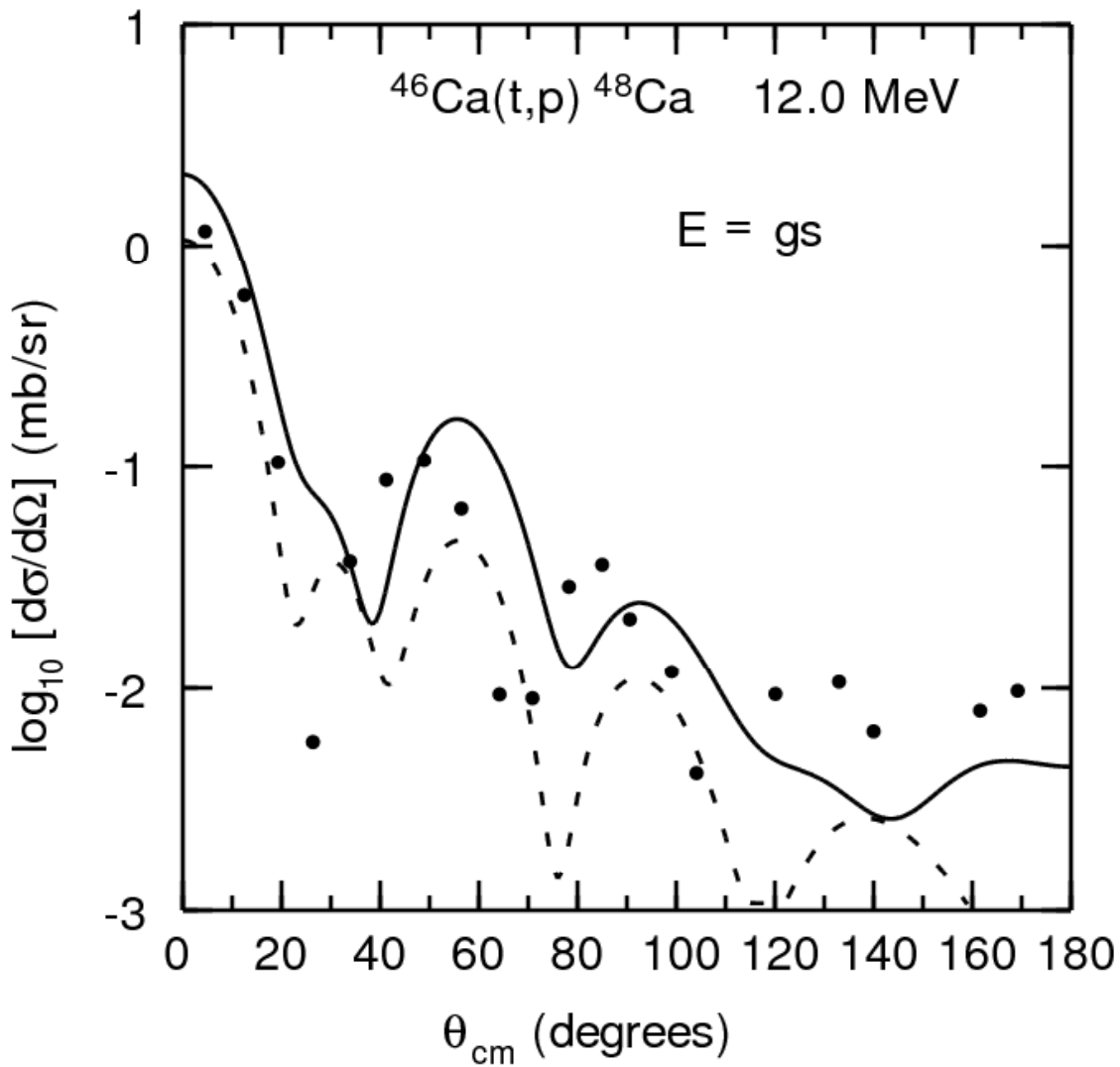

Ca46(t,p) Ca48
Et = 11.96 MeV
Q = 8.75 MeV
E* = 0
(dσ/dω)c.m. - ARB. UNITS
10-2
10-3
10-4
10 30 50 70 90 110 130 150 170
θc.m. (deg)


Ca46(t,p) Ca48
Et = 11.96 MeV
Q = 3.29 MeV
E* = 5.46 MeV
(dσ/dω)c.m. - ARB. UNITS
10-2
10-3
10-4
10 30 50 70 90 110 130 150 170

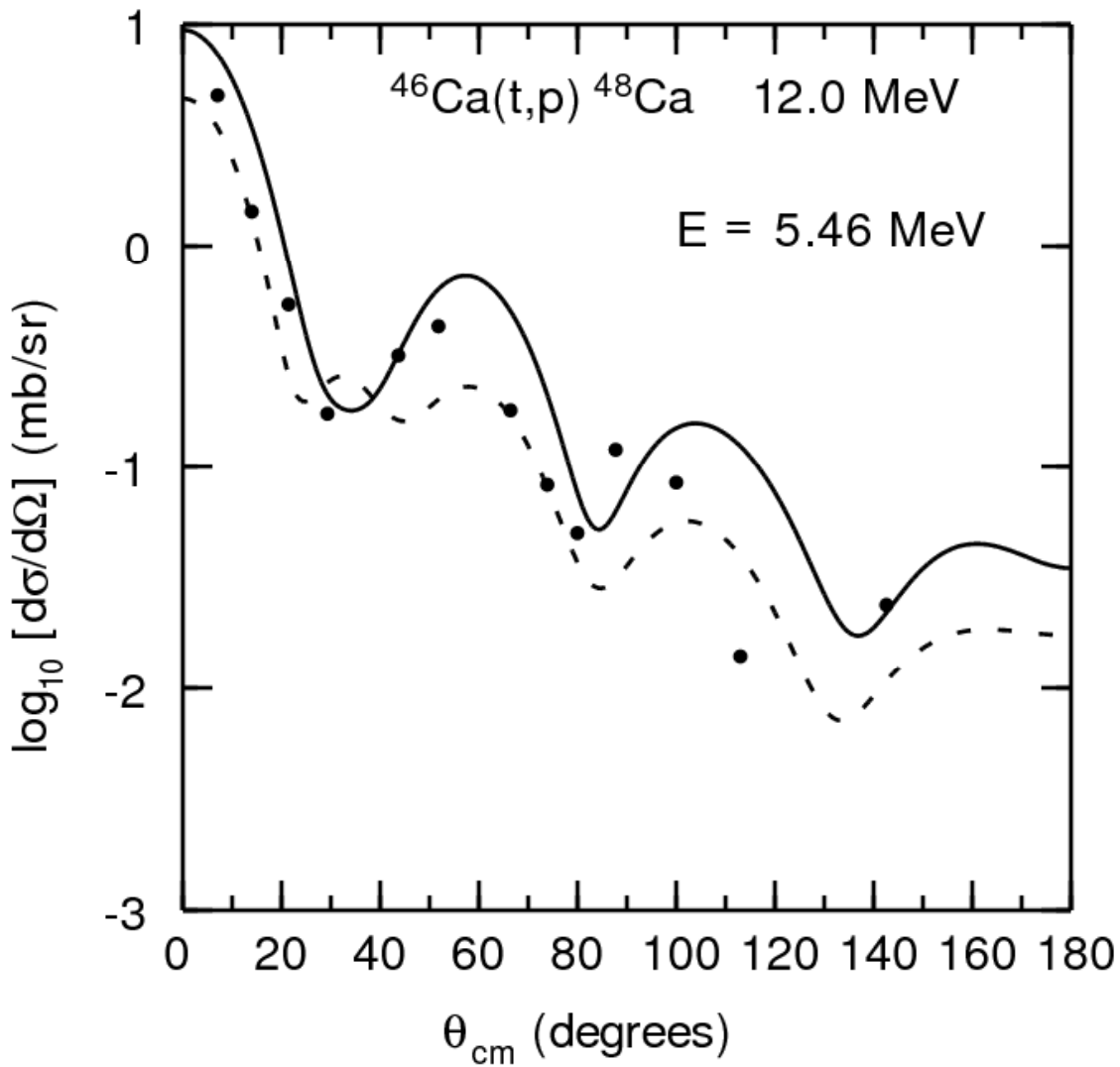
(1) Normal



Examples
$^{12}C(t,p)^{14}C$
$^{46}Ca(t,p)^{48}Ca$
$^{48}Ti(t,p)^{50}Ti$


^{46}Ca(t,p) ^{48}Ca 12.0 MeV
E = gs
$\log_{10}$ [dσ/dΩ] (mb/sr)
θ_{cm} (degrees)
1
0
-1
-2
-3
0
20
40
60
80
100
120
140
160
180

NSCL


^{46}Ca(t,p) ^{48}Ca 12.0 MeV
E = 5.46 MeV
1
0
-1
-2
-3
0 20 40 60 80 100 120 140 160 180
$\log_{10}$ [dσ/dΩ] (mb/sr)
θ_{cm} (degrees)

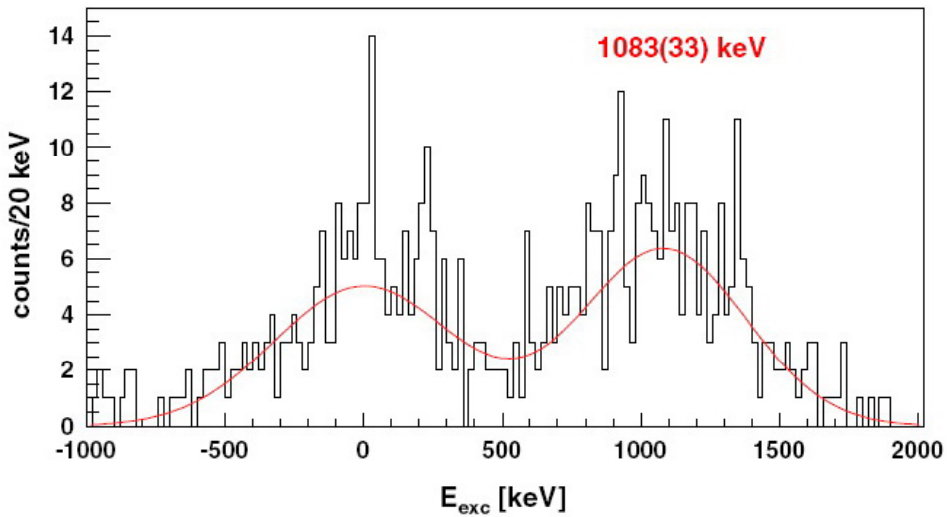
NSCL

$^{30}Mg(t,p)^{32}Mg$

Selected for a Viewpoint in *Physics*
PRL **105,** 252501 (2010) PHYSICAL REVIEW LETTERS week ending 17 DECEMBER 2010

Discovery of the Shape Coexisting 0^+ State in ^{32}Mg by a Two Neutron Transfer Reaction

K. Wimmer,[1] T. Kröll,[1,*] R. Krücken,[1] V. Bildstein,[1] R. Gernhäuser,[1] B. Bastin,[2] N. Bree,[2] J. Diriken,[2] P. Van Duppen,[2] M. Huyse,[2] N. Patronis,[2,†] P. Vermaelen,[2] D. Voulot,[3] J. Van de Walle,[3] F. Wenander,[3] L. M. Fraile,[4] R. Chapman,[5] B. Hadinia,[5] R. Orlandi,[5] J. F. Smith,[5] R. Lutter,[6] P. G. Thirolf,[6] M. Labiche,[7] A. Blazhev,[8] M. Kalkühler,[8] P. Reiter,[8] M. Seidlitz,[8] N. Warr,[8] A. O. Macchiavelli,[9] H. B. Jeppesen,[9] E. Fiori,[10] G. Georgiev,[10] G. Schrieder,[11] S. Das Gupta,[12] G. Lo Bianco,[12] S. Nardelli,[12] J. Butterworth,[13] J. Johansen,[14] and K. Riisager[14]

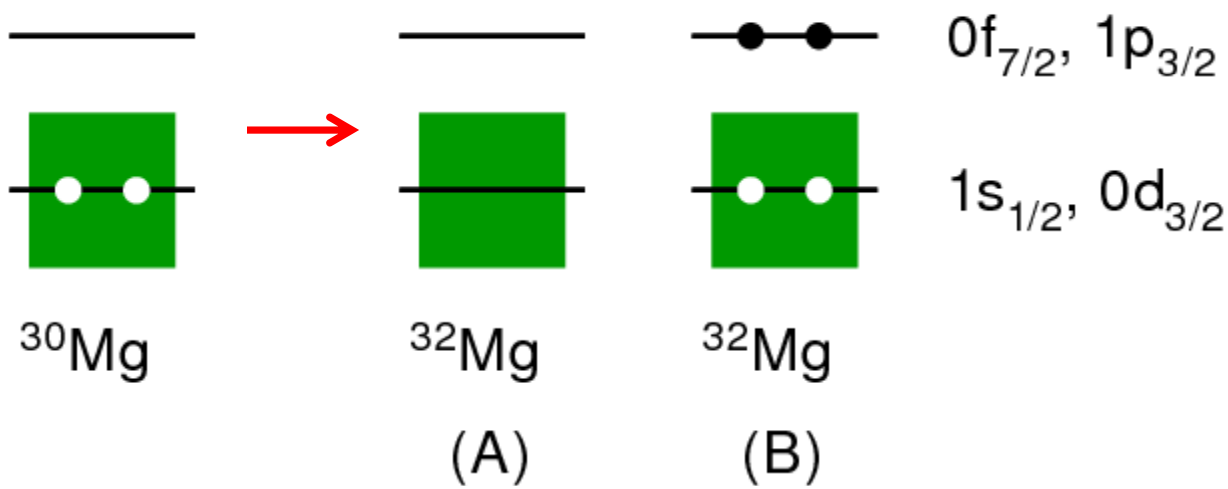


10.5(7) mb 6.5(5) mb

PHYSICAL REVIEW C **84**, 024327 (2011)

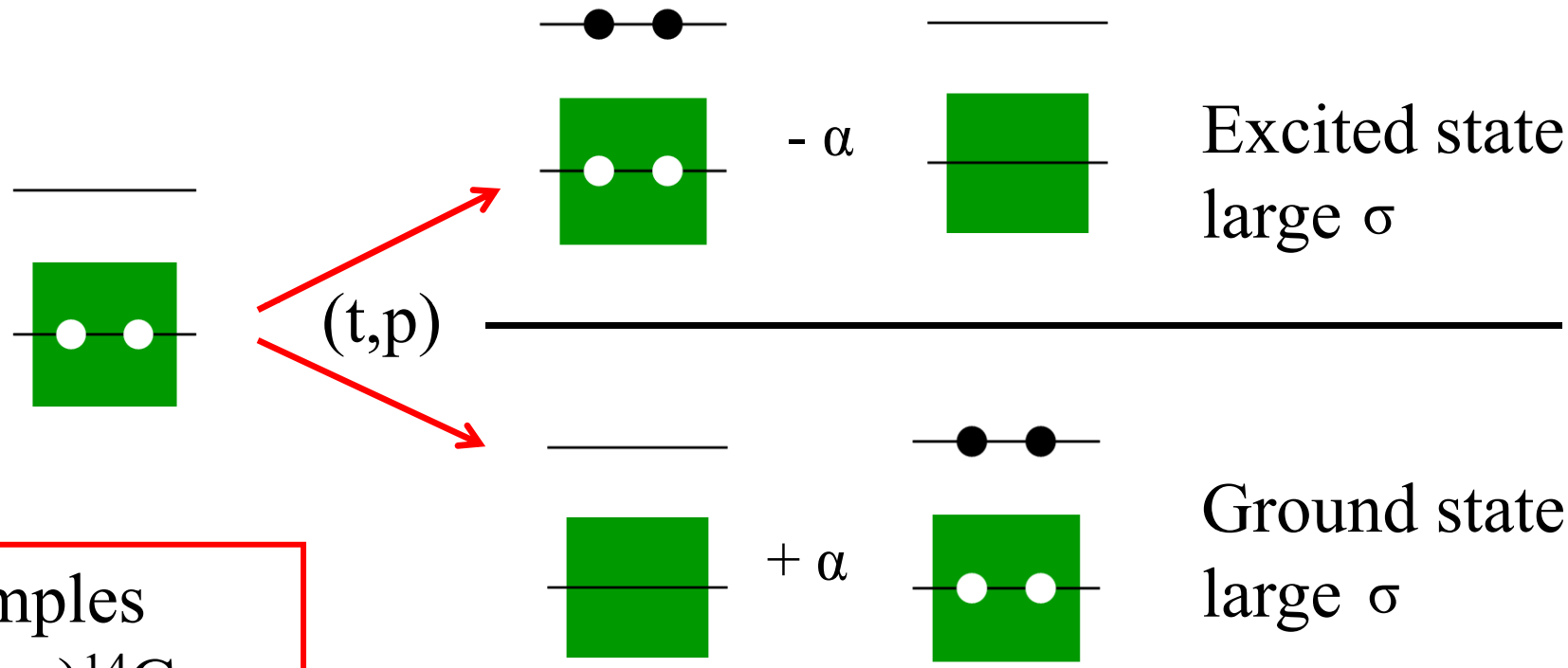
The puzzle of ^{32}Mg

H. T. Fortune



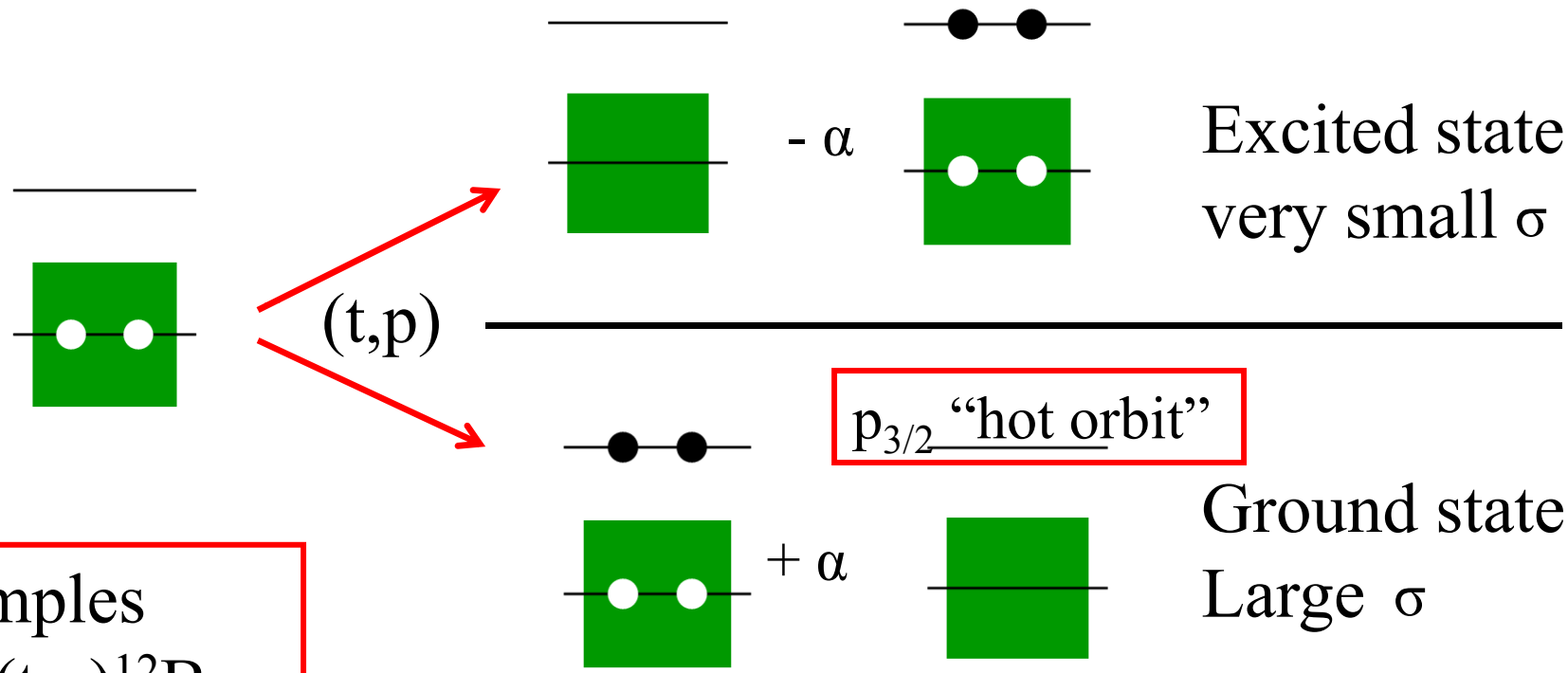
If ^{32}Mg is inside the island of inversion then gs is dominated by (B)

(1) Normal

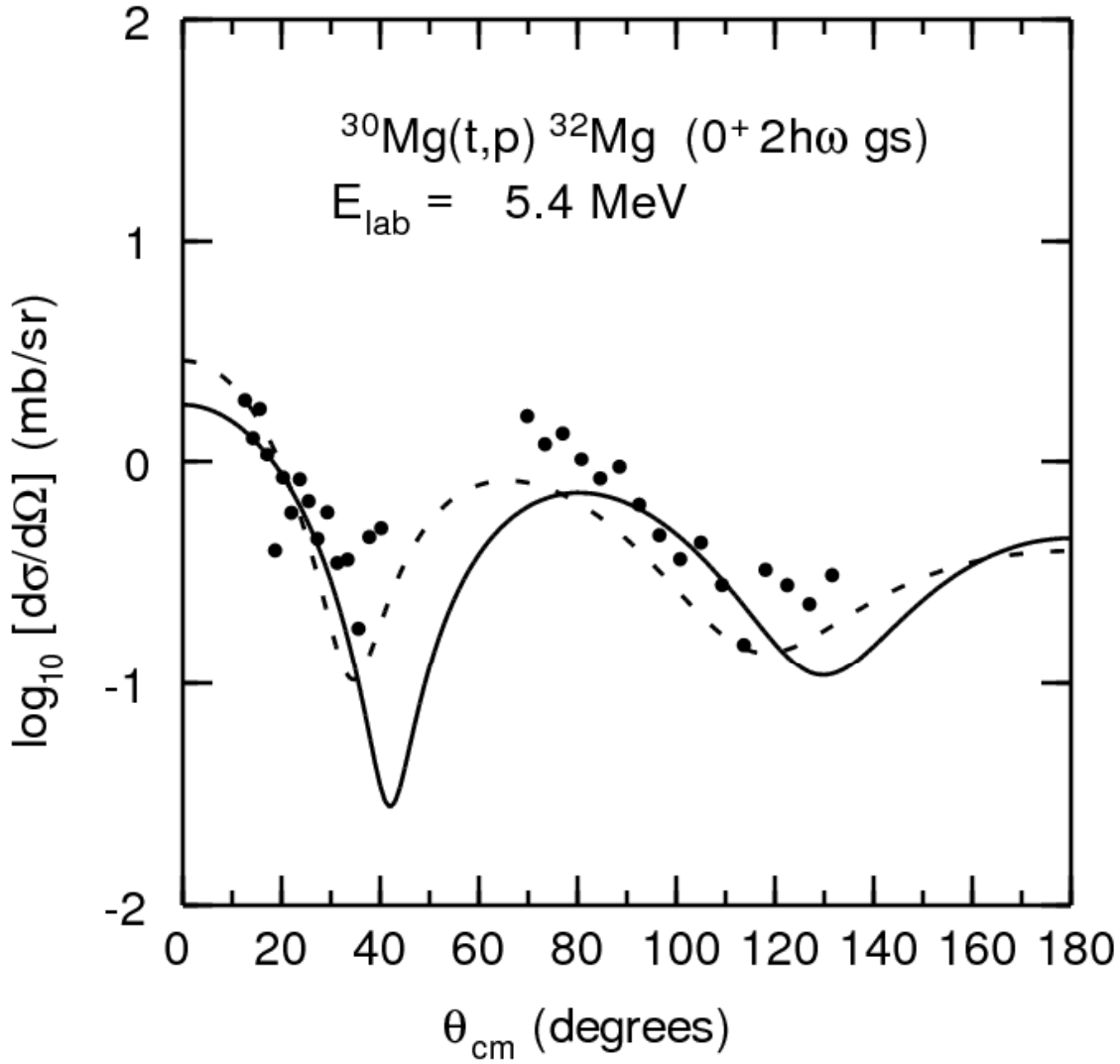


Examples
$^{12}C(t,p)^{14}C$
$^{46}Ca(t,p)^{48}Ca$
$^{48}Ti(t,p)^{50}Ti$

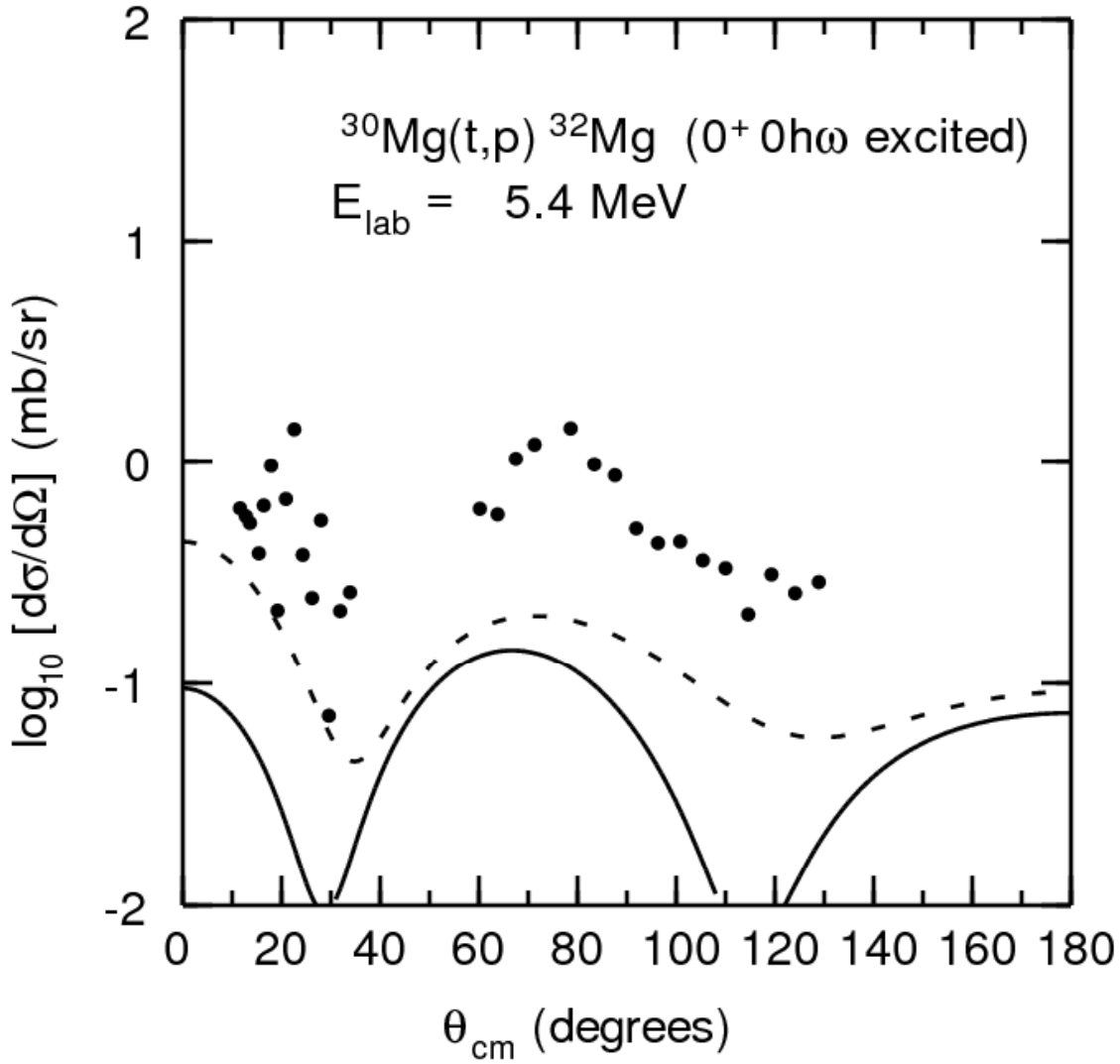
(2) Inverted

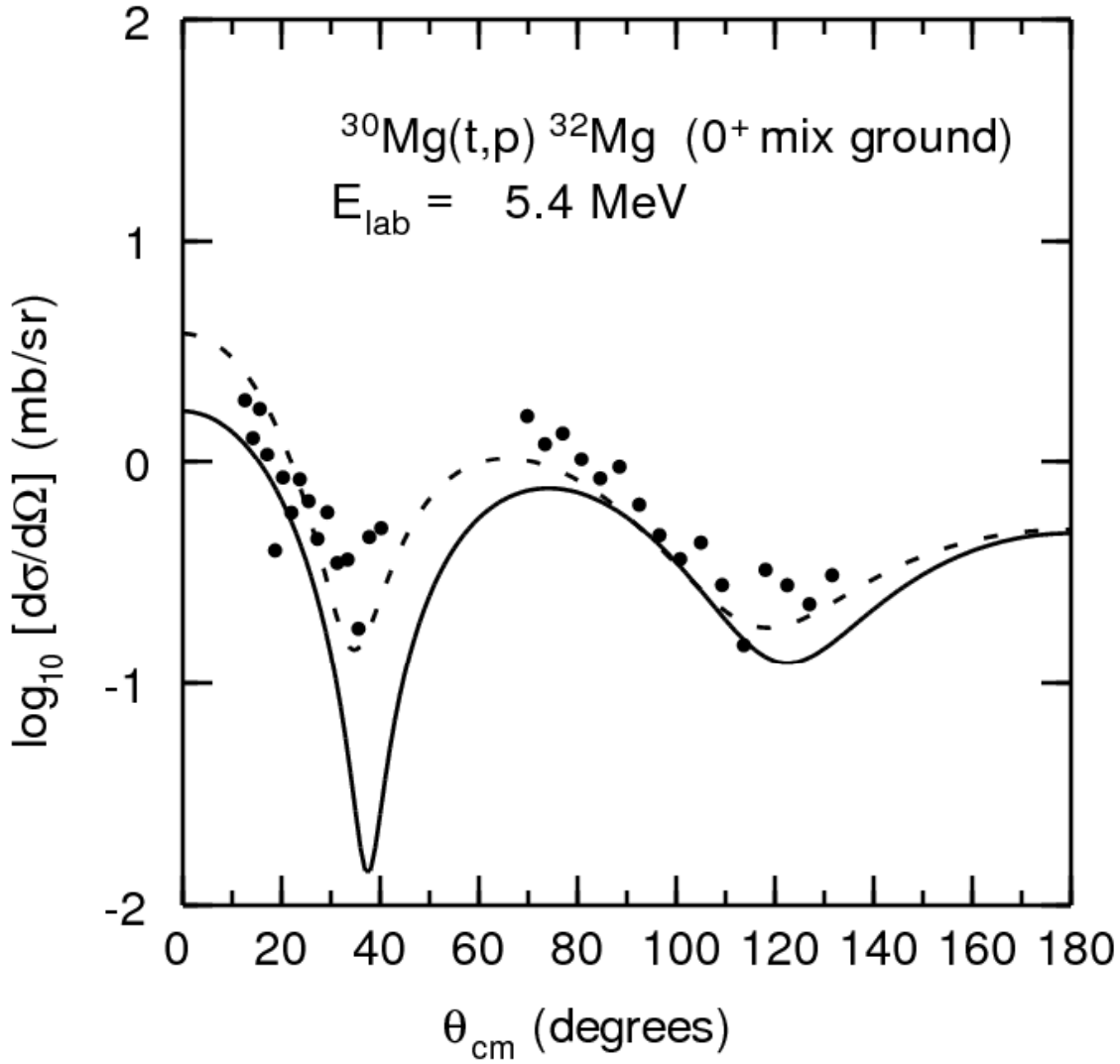


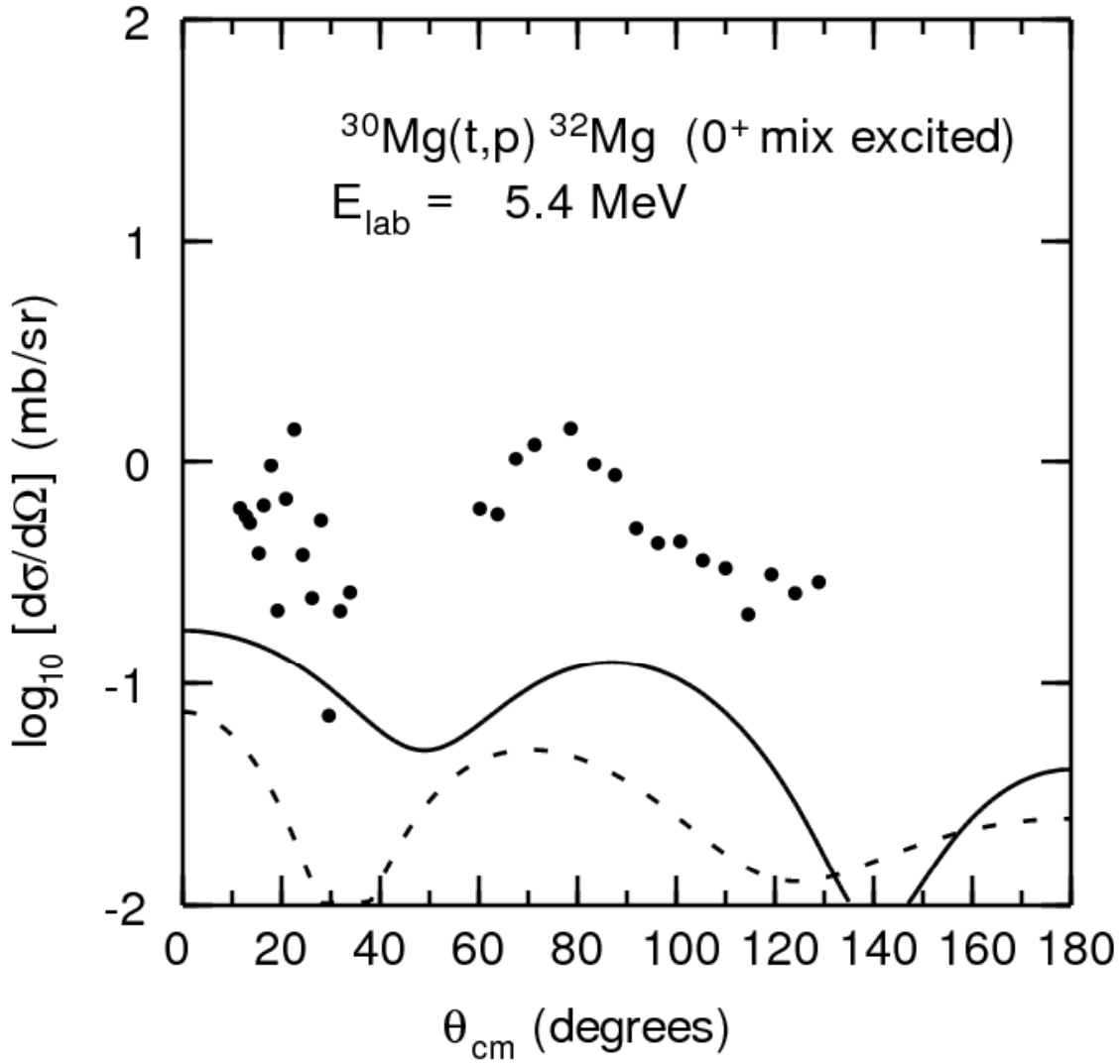
Examples
$^{10}Be(t,p)^{12}Be$

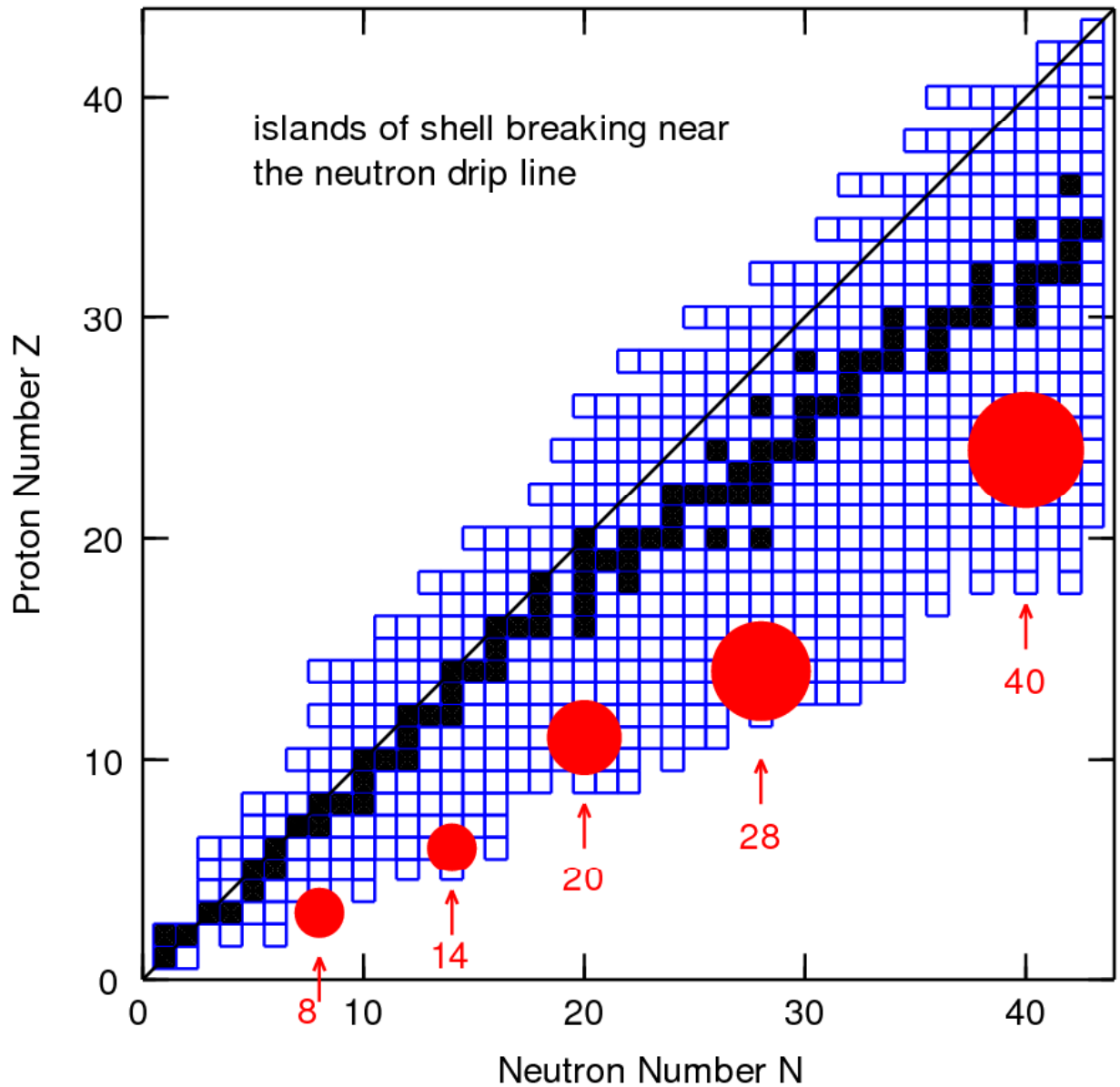

^{30}Mg(t,p) ^{32}Mg (0$^+$ 2hω gs)
E_{lab} = 5.4 MeV
$\log_{10}$ [dσ/dΩ] (mb/sr)
θ_{cm} (degrees)
2
1
0
-1
-2
0
20
40
60
80
100
120
140
160
180

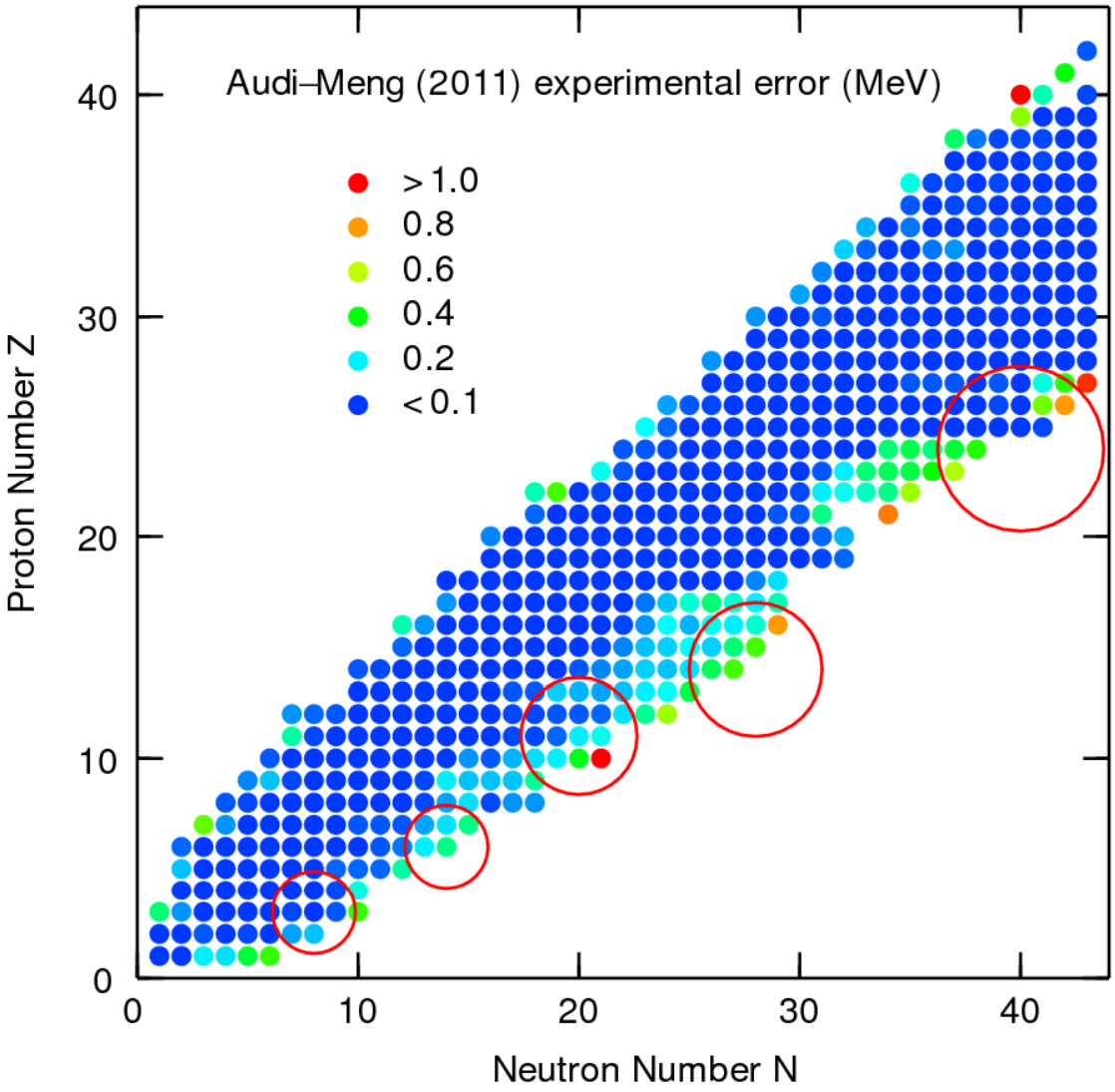
NSCL


^{30}Mg(t,p) ^{32}Mg (0$^+$ 0hω excited)
E_{lab} = 5.4 MeV
$\log_{10}$ [dσ/dΩ] (mb/sr)
θ_{cm} (degrees)
2
1
0
-1
-2
0
20
40
60
80
100
120
140
160
180

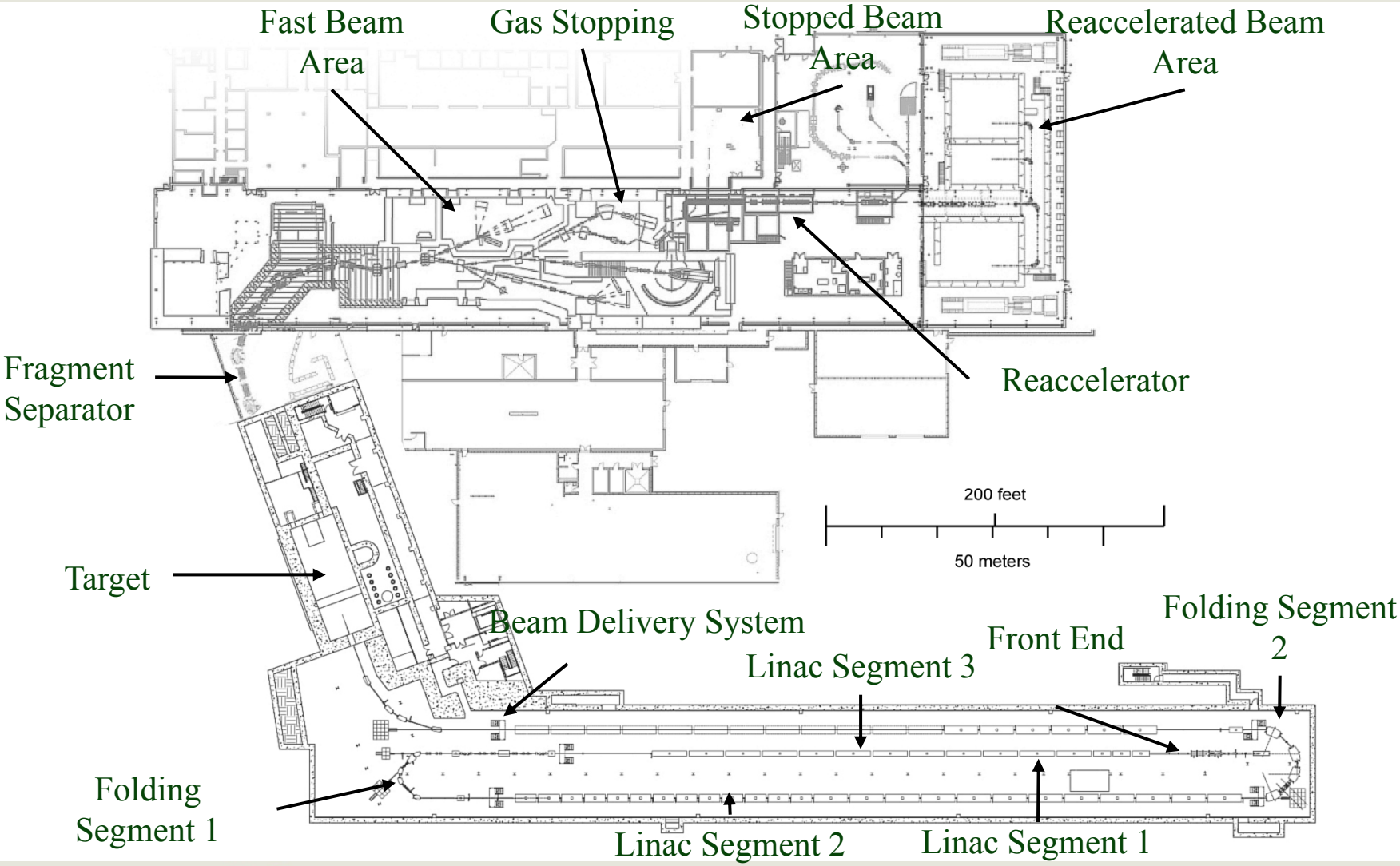

^{30}Mg(t,p) ^{32}Mg (0$^+$ mix ground)
E_{lab} = 5.4 MeV
$\log_{10}$ [dσ/dΩ] (mb/sr)
θ_{cm} (degrees)
2
1
0
-1
-2
0
20
40
60
80
100
120
140
160
180


^{30}Mg(t,p) ^{32}Mg (0$^+$ mix excited)
E_{lab} = 5.4 MeV
$\log_{10}$ [dσ/dΩ] (mb/sr)
θ_{cm} (degrees)
2
1
0
-1
-2
0
20
40
60
80
100
120
140
160
180


islands of shell breaking near
the neutron drip line
Proton Number Z
Neutron Number N
0
10
20
30
40
8
14
20
28
40


Audi–Meng (2011) experimental error (MeV)
> 1.0
0.8
0.6
0.4
0.2
< 0.1
Proton Number Z
Neutron Number N
0
10
20
30
40

FRIB Layout


Fast Beam Area
Gas Stopping
Stopped Beam Area
Reaccelerated Beam Area
Fragment Separator
Reaccelerator
200 feet
50 meters
Target
Beam Delivery System
Folding Segment 2
Front End
Linac Segment 3
Folding Segment 1
Linac Segment 2
Linac Segment 1

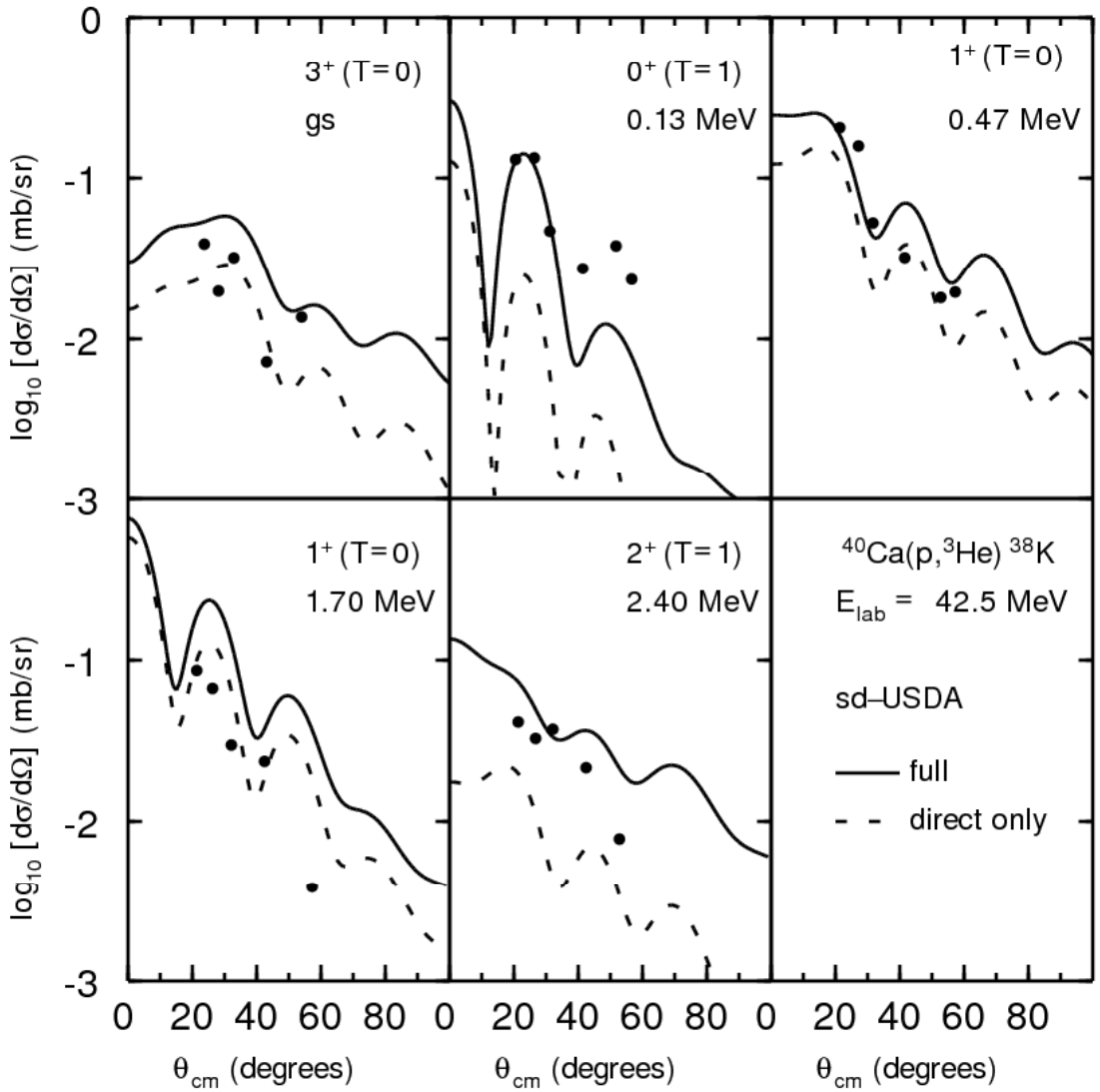
$^{40}Ca(p,^{3}He)^{38}K$

PHYSICAL REVIEW C VOLUME 20, NUMBER 3 SEPTEMBER 1979

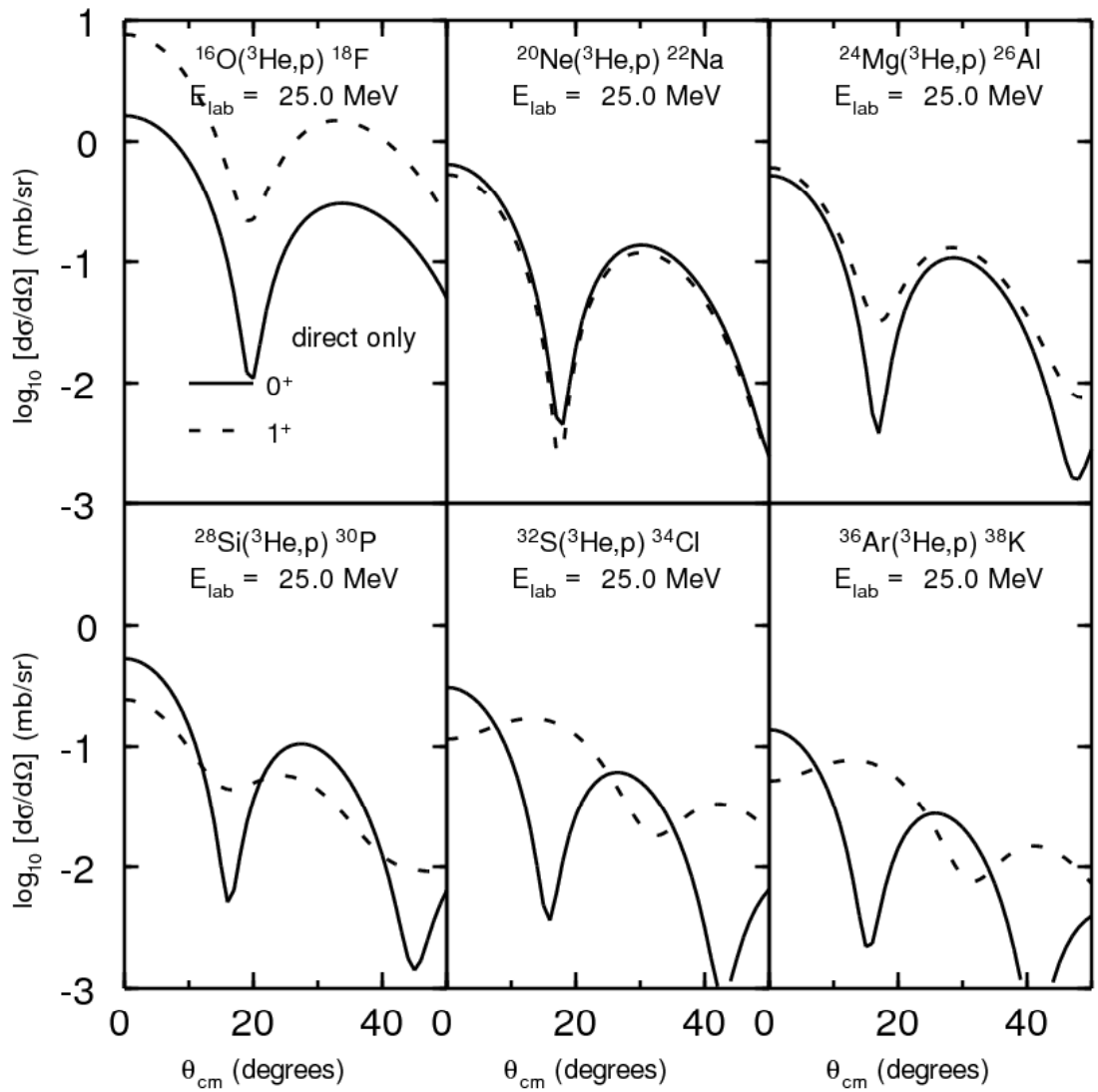
$^{40}Ca(p,^{3}He)^{38}K$ reaction and the low-lying 1^{+}, $T = 0$ states

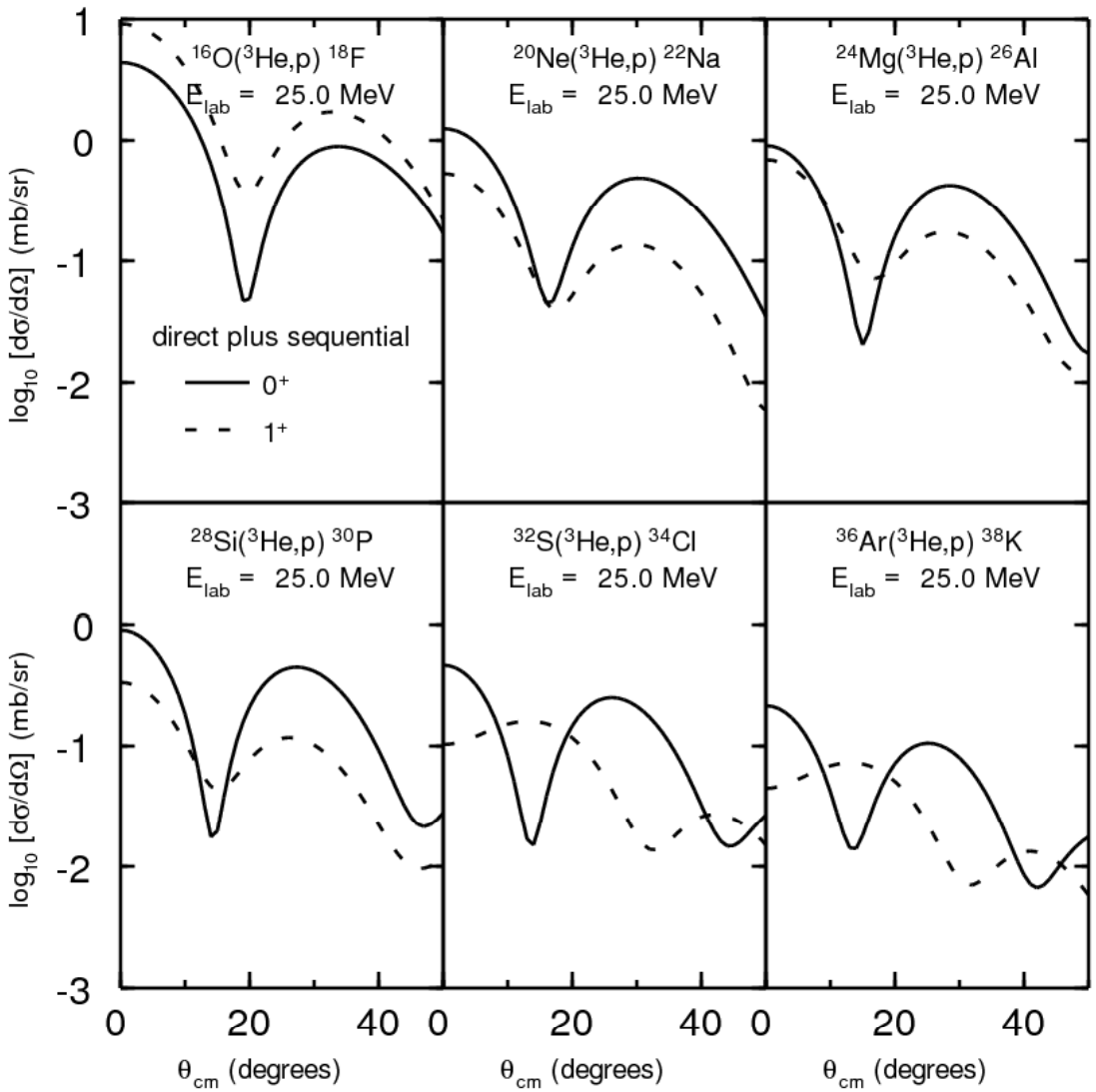
O. Abou-Zeid, , L. Ph. Roesch,* and W. R. Falk
Cyclotron Laboratory, Department of Physics, University of Manitoba, Winnipeg, Canada
(Received 7 May 1979)

Angular distributions to the low-lying states of ^{38}K have been measured in the $^{40}Ca(p,^{3}He)^{38}K$ reaction at 42.5 MeV. Distorted-wave Born approximation calculations for these states, using spectroscopic amplitudes from the wave functions of Wildenthal and Chung, underestimate the 1^{+}, $T = 0$ cross sections, particularly for the 0.46 MeV state.


3+ (T=0)
gs
0+ (T=1)
0.13 MeV
1+ (T=0)
0.47 MeV
1+ (T=0)
1.70 MeV
2+ (T=1)
2.40 MeV
40Ca(p,3He) 38K
Elab = 42.5 MeV
sd–USDA
full
direct only
log10 [dσ/dΩ] (mb/sr)
θcm (degrees)
0
-1
-2
-3
0 20 40 60 80

sd-shell(^{3}He,p) pn-correlations (RIKEN)




$^{16}O(^3He,p)\,^{18}F$
E_{lab} = 25.0 MeV
$^{20}Ne(^3He,p)\,^{22}Na$
E_{lab} = 25.0 MeV
$^{24}Mg(^3He,p)\,^{26}Al$
E_{lab} = 25.0 MeV
$^{28}Si(^3He,p)\,^{30}P$
E_{lab} = 25.0 MeV
$^{32}S(^3He,p)\,^{34}Cl$
E_{lab} = 25.0 MeV
$^{36}Ar(^3He,p)\,^{38}K$
E_{lab} = 25.0 MeV
direct plus sequential
0^+
1^+
$\log_{10}$ [dσ/dΩ] (mb/sr)
θ_{cm} (degrees)
1
0
-1
-2
-3
0
20
40

Concluding Remarks

1) Two-particle transfer reaction including the sequential channels are now easy to do. S=1, T=0 deuteron channel has been included.

2) How important is the S=0, T=1 deuteron channel – will put in as a effective bound state soon…..

3) Global optical potentials usually do not work well.

4) Is it possible to include some (p, t) data in the determination of global optical potentials, or (more importantly) can these potentials be microscopically derived?

5) Two-nucleon transfer reactions will be used to determine the structure and correlations in neutron-rich nuclei - theory must be further improved.

6) It is not easy to understand the present (t, p) data for the excited state in ^{32}Mg.

NSCL